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FINAL REPORT

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FINAL REPORT

Contract No. NAS 9-10747

Title: Development and Testing of a Prototype Operational System for Automatic Monitoring of Sleep during Manned Space Flight

Submitted by: James D. Frost, Jr., M.D.
Associate Professor of Physiology

Names and Addresses of Institutions:

Baylor College of Medicine 1200 Moursund Avenue Houston, Texas 77025	and	The Methodist Hospital 6516 Bertner Boulevard Houston, Texas 77025

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I. SUMMARY OF WORK COMPLETED

A. General

In accordance with the terms of the contract, a prototype operational system for automatically monitoring sleep during manned space flight has been constructed, tested, and delivered to NASA.

B. Description of System (See Fig. 1)

Work carried out previously in this laboratory (NAS 9-9418) resulted in a number of prototype assemblies which accomplished acquisition of EEG, EOG, and head-motion activity, analysis of data to provide an automatic indication of sleep states, and display of the results over time. These basic assemblies have been incorporated into the present operational system with various degrees of modification, and the resultant prototype has been evaluated in terms of its overall suitability for use in a space-flight situation.

1. Recording Cap. Acquisition of EEG and EOG signals is accomplished by utilization of prefilled sponge-type electrodes incorporated into a disposable elastic cap.

2. Preamplifier and Accelerometer Assembly. This unit is attached to the recording cap during use and provides initial amplification for the EEG and EOG activity. A dual-axis accelerometer is included in the assembly and provides information regarding lateral and vertical head movements to the analysis circuitry for use in artifact discrimination.

3. Control-Panel Assembly. This unit is located near the subject during sleep and accepts the signals from the preamplifier cable. Final amplification is provided within this assembly, and the signals are routed to the analog tape-recording apparatus and the automatic-analysis assembly. This assembly also provides a means for automatically testing the cap electrode status (interelectrode resistance for each channel), and proper function is indicated on a front panel display visible to the subject.

4. Analog Magnetic-Tape Recorder. EEG, EOG, and head-motion signals are preserved on analog tape (using the Cook Electric Co. recorder #MSC-REC-SUS-GF-CI) to permit later off-line analysis.

5. Automatic-Analysis Equipment. EEG, EOG, and head-motion signals are processed by the automatic onboard equipment to provide an output signal representative of the subject's current sleep status (awake, stages 1, 2, 3, 4, and REM of sleep). The output is provided in a form suitable for telemetry at a low sample rate (3 bits per 10 sec minimum rate).

6. Ground-Based Display Console. Telemetered sleep-stage information is accepted by this device, which provides a method for rapidly evaluating the sleep states. The current sleep stage is indicated by illumination of an appropriate indicator lamp, and the cumulative time spent in each stage throughout the night is indicated by elapsed-time meters. A stepwise analog output voltage proportional to sleep stage is provided and is utilized to activate the vertical axis of a graphic recorder to provide a continuous profile of the subject's sleep stages over time.

C. Testing Program

A number of all-night recordings have been performed utilizing the entire operational system to determine the compatibility of all subassemblies. Particular care has been taken to ensure that the system does not interfere with the subject's comfort and that the preparation time will be minimal.

II. RECORDING CAP

Although this item is basically the same as that described in the final report for contract NAS 9-9418, several modifications were evaluated in the course of the current contract, and the incorporation of some of these has resulted in a more satisfactory and reliable unit.

A. General

As shown in Fig. 2, the cap, constructed from an elastic (Lycra-type) material, fits snugly on the scalp to provide enough tension to maintain scalp-electrode contact. Proper positioning of electrodes is assured by the fit of the cap around the ears and across the forehead. The padded chin strap, which is secured with Velcro® fasteners, maintains the assembly on the head.

Prefilled, electrolyte-saturated sponge electrodes are attached to the inside of the cap, and the electrode wires are led to a miniature electrical connector at the vertex which allows quick attachment of the preamplifier and accelerometer assembly. Each cap is stored in a sealed polyethylene bag while awaiting use.

B. Electrode Construction

1. General. The shape of a completed prefilled electrode is indicated in the views provided in Fig. 3. This configuration differs from the one originally proposed (Final Report, NAS 9-9418) in that the diameter of the filling and sealing tab has been increased from 2.8 mm to the current 5.1 mm. When the smaller filling tab was used in preparing the cap for use, it was necessary to cut some distance below the tab, on the body of the cone, to

produce an opening of sufficient size (see Fig. 11, Final Report, NAS 9-9418), i.e., the diameter of the tab was not the diameter of the desired opening on the prepared electrode. This required that the subject learn the proper cutting technique through repeated practice.

The new tab size is the same as the required electrode opening, and thus the proper point to make the cut is readily indicated by the junction of the tab and the conical portion of the sponge. A more uniform electrode opening is thus achieved with less effort and skill required of the subject.

As indicated in Fig. 4, the construction of the electrode otherwise remains the same as originally described. Three major parts are identified: 1) the conical, molded silicone-rubber sponge with its apex terminating in the cylindrical filling and sealing tab, 2) a chlorided silver disc and attached insulated wire, and 3) a flat, flexible, wafer-like silicone base which encloses all but one surface of the disc. These three principal components are enclosed by a thin, flexible, vinyl coating which prevents loss of electrolyte when the electrode is stored. After manufacture, the sponge is saturated with electrolyte by injection through a hollow needle which is inserted through the filling tab. After withdrawal of the needle, the tip is resealed with vinyl.

2. Construction Details

a. Silicone-Rubber Sponge

1). 5 cc of liquid silicone-rubber foam base[1] are mixed for 15 sec in a 30 cc disposable, graduated container with 6 drops of catalyzing agent.[2]

2). The foaming mixture is poured into the lower half of a two-part plexiglas mold (pointed object used to force mixture well into tip of mold), and the upper half is then clamped into place.

3). The mold escape port is closed (by sealing the opening with a finger) for about the first 25 sec to achieve slight compression of the sponge structure, then opened during the final 3 min curing cycle.

4). The part is carefully removed from the lower half of the mold, and the conical base is cut away from the portion extending into the escape vent of the upper half, using a thin scalpel blade.

b. Silver-Disc Assembly

1). A 6.37 mm disc is cut[3] from pure silver sheet stock (thickness 0.3-0.5 mm).

2). A 3 in. length of silicone-rubber insulated stranded copper wire[4] is bared for 1/8 in. at one end and attached to the center of one surface of the silver disc, using silver-bearing solder.[5]

3). The solder joint between wire and silver disc is insulated with a silicone-rubber sealant.[6] (Surfaces are initially primed with a precoat[7] and then coated with a self-sealing, free-flowing silicone-rubber compound.[6])

4). The uninsulated surface of the silver disc is chlorided by passing an anodizing current (disc positive, 1.5 V) through the assembly for 10 min while it is immersed in a 0.9% NaCl solution.

c. Silicone-Rubber Base

1). The chlorided silver-disc assembly is positioned in the lower portion of a two-part plexiglas mold and held in place with a small piece of double-sided adhesive tape.

2). 5 cc of liquid silicone rubber[8] are thoroughly mixed with 2 drops of catalyzing agent[9] in a 30 cc disposable, graduated container.

3). The catalyzed liquid silicone rubber is poured into the lower cavity of the two-part plexiglas mold, taking care that no air bubbles are trapped around the silver-disc assembly.

4). The upper half of the plexiglas mold is positioned, and the two halves of the mold are clamped together during the required curing time (approximately 6 min).

5). The cured part is removed from the mold, and any excess rubber is carefully trimmed off. The exposed, chlorided surface of the silver disc is cleaned with a xylene solution to remove all traces of silicone rubber and other contaminants.

d. Final Assembly

1). The sponge unit is attached to the base assembly using a silicone-rubber adhesive.[6] (Note: Care must be taken not to allow the adhesive to cover the chlorided silver disc, which must directly contact the sponge material.)

2). When fully cured (at least 24 hr after application of adhesive), the entire assembly is dipped into a red liquid vinyl material[10] which air dries (approximately 24 hr) to form a thin (0.002-0.003"), flexible, insulating and moisture-retaining film over the entire electrode.

3). A final coat is applied by dipping the electrode into a clear liquid vinyl[11] and air drying as in 2). This final coat improves the pliability of the completed assembly.

e. Prefilling Procedure

1). The vinyl material covering the tip of the filling-and-sealing tab is removed, exposing a small area of the silicone-rubber sponge.

2). A hollow injection needle, which is connected to a pressurized supply of electrolyte solution,[12] is inserted through the exposed tip into the interior of the electrode. Enough electrolyte solution is injected to ensure complete saturation of the entire sponge, and the needle is withdrawn.

3). The exposed sponge tip is resealed with liquid vinyl, thus preventing further loss of electrolyte and allowing the electrode to be stored indefinitely.[13]

C. Cap Construction

1. General. The recording cap is constructed from several parts of nylon-spandex fabric (XK-56292 or equivalent, Ashaway Textile Mills), as illustrated in Fig. 5. Although the caps may be individually tailored for the individual subject, three basic sizes have been developed during the current contract period, and it has been found that essentially all subjects can be accommodated by one of these standard configurations. (See Fig. 6 for a comparison of the large, medium, and small dimensions.)

2. Construction Details. The individual pieces (Fig. 5) are sewn together as indicated in Fig. 7, using elastic thread to preserve the elasticity of the completed unit. Seams are maintained at approximately 1/4", and the free edges of fabric are hemmed (allowing approximately 1/4" for hem). Velcro® patches are sewn into place (Fig. 7) to provide attachment points for the preamplifier assembly at the vertex and the chin strap below and anterior to the ears. A gripper-type snap fastener is affixed to the cap 1" behind the vertex Velcro® to hold the preamplifier-cable assembly (described below). The chin strap is constructed as a hollow, flattened tube, and contains a strip of foam rubber throughout its length for added comfort.

D. Electrode Placement

1. Standard Configuration. Seven electrodes are utilized: four for EEG (C_1-O_1, C_2-O_2, according to the ten-twenty system of the International Federation, Electroenceph. Clin. Neurophysiol., 1958, 10: 371-375), two for EOG (left lateral canthus and central forehead), and one frontally located ground (see Fig. 8). This arrangement provides for two central-to-occipital EEG channels and one EOG channel which registers both right-left and up-down eye movements. An example of a recording made from a subject wearing such a cap is shown in Fig. 9.

2. Alternate Configuration. Visual interpretation of polygraphic recordings of sleep is aided by the addition of a channel displaying the electroencephalographic activity of the submental musculature. Although the currently proposed automatic sleep-analyzer scheme does not utilize EMG, it may be desirable in some cases to include this information on the analog tape so that this measurement may be evaluated during off-line playback and visual analysis of the data.

The feasibility of such recordings utilizing prefilled sponge electrodes incorporated into the chin strap of the recording cap was verified in a number of all-night tests. As illustrated in Fig. 10, one EEG channel has been eliminated so that no change in the preamplifier or following stages is necessary. An example of a recording made using such a cap is provided in Fig. 11.

E. Preparation of Electrode Cap for Use

Immediately before the recording period is to begin, the subject removes the cap from its plastic bag and attaches the preamplifier and accelerometer assembly, using the electrical connector and Velcro® patch near the vertex. The sealing tab is then clipped off each electrode, as illustrated in Fig. 12, and the cap is donned and secured with the chin strap. Each electrode is rocked slightly to position the exposed sponge tip against the scalp through the hair, and correct operation is verified by the automatic electrode-test circuit on the control-panel assembly. In a large number of laboratory trials, it has been determined that the entire preparation procedure as outlined above can easily be accomplished by the subject himself in 3 min. While this time may be lengthened slightly by difficulties associated with the weightless condition during actual space flight, the time should under no circumstances exceed 5 min.

Post-recording "breakdown" time is only about 1 min, since it is only necessary for the subject to remove the cap and discard it (i.e., a new cap is provided for each recording period).

III. PREAMPLIFIER ACCELEROMETER AND CONTROL PANEL

A. General

As described previously, the preamplifier-accelerometer unit provides initial amplification of the EEG and EOG signals in addition to supplying information regarding motion of the subject's head. As illustrated in Fig. 2, this assembly is fastened to the recording cap near the vertex of the head, where minimal interference with the subject's comfort is assured. The amplified signals pass through a 4' cable connected to the control-panel assembly, which provides final amplification of the signals in addition to the necessary subject operational controls and the electrode-testing circuitry. These two assemblies are powered by batteries during operation, and the batteries are automatically recharged by the power system when the unit is not in use. The physical configuration of the prototype system is illustrated in Fig. 13.

B. Circuitry

Since the preamplifier-accelerometer and the control-panel units are greatly interrelated electronically, the circuit is described here as a single unit. The physical separation of the various components is, however, indicated in the accompanying diagrams.

1. Amplification Circuitry

a. As shown in Fig. 14, initial amplification of EEG and EEG signals is accomplished in the preamplifier. Q_2 and Q_3, a matched pair of N-channel field-effect transistors (Texas Instruments, TIS69) are arranged in a differential input configuration and accept the unamplified signal from the electrodes. Q_1 supplies a constant current to the common-source junction of Q_2 and Q_3 to provide improved rejection of common-mode signals which may appear at the inputs. R_1, in the base circuit of Q_1, is adjusted so that the drain voltage of Q_2 and Q_3 is approximately +5 V (referred to ground) when both inputs are shorted to ground. Two diodes (IN914) are provided in the common-source circuit of Q_2 and Q_3 to prevent flow of current between Q_2 and Q_3 during the electrode-testing mode of operation (see below). The initial stage of amplification provides a gain of approximately 10 and supplies a signal of low output impedance ($\sim 1500\Omega$) to the following stage.

The preamplified EOG and EEG signals are led to the final amplification circuitry located in the control panel through individually shielded, flexible cables.[14]

Final amplification is accomplished by the Fairchild type 709 operational amplifier,and the associated filter circuits limit the bandwidth to the specified range.

b. Measured Specifications

Input impedance: greater than 1000 x $10^6 \Omega$
Output impedance: $\sim$ 200 Ω
Common-mode signal rejection: $\sim$60 dB
Gain: x 1000
Frequency response: 0.11 Hz-40 Hz (-6 dB)
Noise level (referred to input): 3 μV peak-to-peak

2. Accelerometer Circuitry. As indicated in Fig. 14, a dual-axis accelerometer and associated amplification circuitry are included within the preamplification unit and are utilized to provide information concerning motion of the subject's head. Signals from the accelerometer are amplified by the field-effect transistor (TIS68) and led to the control-panel assembly through flexible shielded cable.[14] The accelerometer circuitry is shown in isolated form in Fig. 15A.

The accelerometer and the associated FET are located within a small aluminum cylinder (see Fig. 15B, construction view) which serves as an electrical shield to reduce the unit's susceptibility to extrinsic inductive and capacitive influences. The accelerometer itself is an Astatic #1K7B stereo crystal cartridge which has been modified by the addition of a 0.08 gm mass at the tip of the recording stylus.

As indicated in Fig. 15C, the accelerometer is oriented within the preamplifier assembly so that its axes of maximal sensitivity are aligned in the vertical (i.e., up-down) and lateral (i.e., side-to-side) directions when the preamplifier is correctly mounted on the recording cap.

3. Electrode-Test Circuitry

a. General. This section of the control-panel assembly is designed to perform automatic testing of each of the recording electrodes before the sleep period begins. The control panel, easily visible to the subject during application of the cap, contains a series of indicator lamps, each representing one of the sponge-electrode sensors on the cap. When the cap is donned by the subject, he moves the panel-selector switch from the "off" position to the "test" position, thereby activating the automatic test circuitry. A small test current (0-10 μA) is passed through the ground electrode to each of the 6 recording electrodes, and this current is sensed to provide an indication of interelectrode resistance. If a given electrode is in proper contact with the scalp, its average resistance will be 50,000Ω or less, and this condition is indicated by illumination of the corresponding lamp in the simulated control-panel display. Improper contact can usually be resolved by slightly rocking the sensor to reposition the sponge through the hair and against the scalp.

b. Circuit Details. Operation of the electrode-test circuitry is illustrated in isolated form in Fig. 16. In this mode of operation, the input N-channel field-effect transistors (FETs) in the preamplifier are disconnected from the remainder of the amplification circuitry and connected to the test circuitry by the mode switch, as shown. All FET drains connect to point A (see Fig. 16) through 1 MΩ potentiometers. Each FET gate connects, as usual, to an individual electrode on the recording cap, and the electrodes in turn make contact with the subject's scalp. A single cap electrode serves to ground the subject to the system common ground.

In the normal recording mode, the FETs are used as amplifiers, and the drain and source points are always biased positive with respect to ground, thus keeping the gate-source/drain junction reverse-biased, resulting in no significant current flow (high input impedance). In the electrode-testing mode, as indicated in Fig. 16, the drains are periodically driven negative with respect to ground by the 1 Hz oscillator circuit, composed of Q_1 and Q_2 and associated components, which is connected to point A. When point A goes negative, the FET gate-drain junction is biased in a forward direction, permitting current flow from gate to drain. The current pathway is illustrated in detail for one electrode of channel 1 in Fig. 16. If the cap ground electrode and the EOG electrode are both in contact with the subject's scalp when point A goes negative, current will flow from the circuit ground, through the two involved electrodes (Re = electrode-to-scalp impedance), across the forward-biased gate-drain junction, and through the 1 MΩ potentiometer in the sensing circuit to point A. The amount of current passing through the 1 MΩ resistor, and thus the voltage developed across it, will depend upon the interelectrode impedance (Re) at the scalp. As Re becomes lower (i.e., the better the electrode contact), the voltage developed across the sensing resistor increases.

The FET in the sensing circuit, Q_3, detects and amplifies the voltage developed across the 1 MΩ resistance. The amplified voltage serves to turn the following stage, Q_4, fully on when Re drops below 100,000 (each electrode averages 50,000Ω, indicating adequate scalp-electrode contact). Q_4 drives the final stage, Q_5, which, in turn, operates the panel-indicator lamp for the appropriate recording electrode. A separate sensing circuit exists for each of the 6 recording electrodes, and the indicator lamps are arranged in a display simulating the cap-electrode configuration, permitting the subject to rapidly identify the faulty electrode. If the common-ground electrode on the cap is at fault, no sensing circuit will operate, and all indicator lamps will be extinguished.

4. Power System. As illustrated in Fig. 17, the control-panel assembly is powered by four 6 V rechargeable batteries. In the "off" position, as shown in Fig. 17, each of the batteries is recharged by the current-regulator circuitry and held at full charge until needed.

IV. ANALOG MAGNETIC-TAPE RECORDER

As indicated in Fig. 14, the EEG, EOG, and head-motion signals are led to the onboard recorder where they are preserved in unprocessed form for later off-line analysis. The recorder used in this prototype system is the NASA Biomedical Recording System (MSC-REC-SYS-GF-C1) which was developed by the Cook Electric Co. for use in the Gemini program and which is described in detail in the manual supplied as a part of NASA contract NAS 9-5199.

The recorder is capable of recording 7 channels of data (although only 4 are used in this apparatus) on 1/2" magnetic tape with a frequency response of 0.1 to 100 Hz and will operate continuously for up to 100 hr on one reel of tape.

The amplified EEG and EOG signals from the control-panel assembly are supplied to the recorder (see Fig. 14) after attenuation to provide the necessary input level of ± 10 mV. The output signal from the accelerometer amplifier is of adequate magnitude to be recorded directly, and it enters the recorder through a 25 μF capacitor which eliminates the DC bias level.

Each channel of the recording system must be carefully adjusted during the preliminary check-out procedures to assure that the DC offset compensation within the recorder provides a zero-level output signal to the recording heads when a zero-level signal is present at the inputs of the appropriate data channels. (Refer to recorder manual, NASA contract NAS 9-5199.)

V. AUTOMATIC DATA-ANALYSIS CIRCUITRY

A. General

The goal of the onboard data-analysis scheme is to provide an output which is indicative of the subject's current sleep state and is suitable for telemetry to the ground-based display console. The input for the automatic analyzer consists of the following:

1 EEG channel (central-to-occipital electrode pairs)
1 EOG channel (left-lateral canthus to central-forehead electrode pairs)
1 dual-axis accelerometer channel (head motion along the vertical and lateral axes)

The output of the analyzer is a voltage which is restricted to one of seven possible levels, each corresponding to a predetermined sleep-state category.

Output Voltage	Sleep State	Description
0.929 V	Awake	The non-sleep state, characterized by alpha activity (8-12 Hz) and/or a low-amplitude mixed-frequency activity in the EEG.
1.561 V	Stage 1 sleep	The lightest stage of sleep in terms of ease of arousal and characterized by low-amplitude EEG signals of a predominantly lower frequency (5-7 Hz) than the awake state. Occasional vertex transient forms of up to 200 μV may be present.
2.194 V	Stage REM sleep	Characterized by rapid eye movements (REMs) as detected by the EOG and, concurrently, EEG signals which appear much like those of stage 1 but with less prominent vertex transient forms.
2.826 V	Stage 2 sleep	Characterized by occasional bursts of 14 Hz EEG potentials (spindles) and/or K complexes (relatively high-voltage transients exceeding 0.5 sec duration) superimposed on a somewhat random, low-amplitude background signal.
3.459 V	Stage 3 sleep	Relatively high-amplitude (greater than 75 μV) activity of 2 Hz or slower is present between 20 and 50% of the time. Intervening activity is relatively low in amplitude. 14 Hz spindles may be present.
4.091 V	Stage 4 sleep	Relatively high-amplitude (greater than 75 μV) activity of 2 Hz or slower is present more than 50% of the time. 14 Hz spindles may be present.
4.723 V	Stage 0	A null state to indicate interruption of the data or other loss of normal physiological signals.

Operation of the automatic analyzer is indicated in a simplified form in Fig. 18, which illustrates the various logic functions involving the three input signals. A detailed schematic diagram of the prototype analyzer is provided by Fig. 19.

B. EEG Analysis (Refer to Fig. 18, section 1, and Fig. 19)

The EEG-analyzer portion is essentially an amplitude-weighted, dominant-frequency meter for the 0.7 to 13 Hz EEG band.

As indicated in Fig. 18, amplified EEG activity enters the analyzer circuitry and is first passed through a band-pass filter which limits the response to the 0.7 to 13 Hz range. This step greatly attenuates electrode, movement, and muscle artifacts but retains enough EEG information to allow accurate determination of sleep stages.

The signal next enters three level detectors, each set to indicate a different EEG amplitude (see Fig. 20). Level 3 is greatest, arbitrarily called 100%. Level 2 is at 20% of the distance from the base line to level 3, and level 1 is at 1%, just above the noise level of the system. The gain of the preamplifier is adjusted once for each subject so that only the greatest amplitude, negative-going waves in his eyes-closed waking EEG exceed level 3, with the average peak amplitude falling midway between levels 2 and 3 (i.e., approximately 60%). Thus, the higher-voltage activity during sleep will frequently cross the 3rd level, whereas the low-voltage activity during stage 1 will exceed only levels 1 and 2.

The logic circuitry (Fig. 18, bistable circuit, logical AND gate) associated with the level 1 and 2 detectors triggers a negative-pulse generator if, and only if, level 1 and level 2 are crossed successively in a negative-going direction (e.g., Fig. 20, A-E, I, J). Fluctuations about either level 1 or 2 alone are ineffective (Fig. 20, E, F). As a result, the number of pulses produced by the negative-pulse generator is proportional to the dominant frequency of the EEG and independent of minor variations or inflections. Each pulse from the negative generator is of a constant amplitude and duration.

The level 3 detector operates in a straightforward fashion, triggering the positive-pulse generator each time it is exceeded (Fig. 20, G, H). The output of the positive-pulse generator is of the same duration as that of the negative generator, but of opposite polarity and one-half the amplitude. The pulses from the two generators enter the mixer amplifier, which supplies a composite pulse train to the integration circuit (see lower tracing, Fig. 20).

The integrator is a buffered RC circuit with a 10 sec time constant for both rise and decay. The output is consequently a voltage level that is dependent upon the number and polarity of pulses received during the preceding approximately 10 sec.

If only levels 1 and 2 are exceeded by the fluctuating EEG input voltage, then the integrator's output is proportional to the dominant frequency. However, each time level 3 is exceeded (one-half amplitude, positive pulse), the integrator loses one-half the value previously added by a level 1-2 pulse (negative pulse).

In terms of its influence on the output of the integration circuit, an EEG wave of very low voltage, i.e., not exceeding level 2, has zero value, an intermediate-amplitude wave has maximum value, and a high-amplitude wave (exceeding level 3) has a value of 50%, since it produces both a negative pulse and a positive pulse of one-half the amplitude. When a subject is awake, the EEG voltage is sufficient to cross levels 1 and 2 and is relatively high in frequency. The output of the integration circuit will then be at its highest value. When the EEG pattern changes to stage 1, the amplitude is lower, and the frequency declines, both factors resulting in fewer crossings of levels 1 and 2 and a corresponding decrease in the output voltage level from the integrator. In stage 2, transient EEG forms exceed level 3, and the dominant frequency is still lower, again resulting in further reduction of the integration circuit output level. During stage 3 and into stage 4, progressively more waves of low frequency reach level 3, and the output level declines to its lowest normal value.

Certain abnormal conditions can produce even lower levels, for example the oscillations of deep coma, and if the EEG becomes flat or the signal is lost, the lowest possible level (0 V output) is reached, since no pulses will be supplied to the integration circuit.

The EEG state of the individual is therefore expressed as a voltage level at the output of the integrator: the awake EEG is associated with the highest output voltage, and progressive stages of sleep are accompanied by correspondingly lower output values.

The analog output of the integrator enters a series of dual-comparator circuits in the sleep-stage-output section (Fig. 18, section 4), where it is compared with previously determined voltage ranges, each corresponding to a discrete clinical stage (awake, stage 1, 2, 3, 4, or abnormal). Initial setting of the range potentiometers is accomplished by determining the output voltages from the integrator that correspond to the transition points between EEG sleep stages.

These values have been determined empirically by running a number of all-night sleep records simultaneously on a conventional EEG machine and on the automatic analyzer. As the subject progresses from one stage to another by visual-scoring criteria, the appropriate potentiometer is set for the correct value of the integrator output voltage. These experimentally derived transition points may be more easily expressed in terms of the frequency of a sinusoidal test signal applied to the EEG input as in the following table.

Transition		Frequency of Sine-Wave Signal Crossing Levels 1 and 2 but not 3
From	To	
Awake	1	5.0 Hz
1	2	3.8 Hz
2	3	2.3 Hz
3	4	1.8 Hz
4	0	0.61 Hz
0	4	0.74 Hz
4	3	2.1 Hz
3	2	2.6 Hz
2	1	4.1 Hz
1	Awake	5.3 Hz

This table is useful for initial calibration of the analysis instrument, since it may be accomplished with commercial test equipment. (It should be noted that this procedure is not performed for each subject.)

The "hysteresis" which is evident in the above table (e.g., the difference in the transition point between stages as the frequency is increased as opposed to the case when the frequency is decreased) is necessary to prevent rapid oscillations between stages when the integrator output is close to the transition point, and in addition this feature duplicates, to some extent, the same behavior noted in human visual analysis. This function is controlled by the value of the feedback resistor between pins 9 and 6 of the dual-comparator circuits (see Fig. 19, section 4).

C. EOG Analysis (See Fig. 18, REM detection section; Fig. 19, section 3)

1. Purpose. The basic function of the EOG-analysis circuitry is to recognize the occurrence of rapid eye movements (REMs) which occur during stage 1 or 2 of sleep, as indicated by the EEG-analysis circuitry. If a REM is detected during EEG stage 1 or 2, the analyzer-output circuit indicates the presence of stage REM sleep.

2. Background. It has been determined experimentally that the EEG-analysis circuitry alone classifies stage REM sleep as either stage 1 or stage 2 sleep. In most instances, the EEG analyzer indicates a continuous fluctuation between stage 1 and 2 throughout a REM period, reflecting the transient changes in delta-frequency components. During true stage REM sleep, an electro-oculographic recording indicates occasional sharp transient forms reflecting brief bursts of rapid, jerky movements of the subject's eyes. Although these events are sporadic throughout the REM period, they usually occur with a frequency of at least one recognizable event in each 30 sec epoch. During true stage 1 or 2 sleep, these events are absent, indicating no rapid movements of the subject's eyes.

The function of the EOG-analysis circuitry described below is to detect EOG events which may be REMs, eliminate certain artifactual signals, and provide a continuous indication of the presence of REM as long as one acceptable event per 30 sec is detected while the subject's EEG characteristics are those of stage 1 or 2.

3. Theory of Operation and Construction of Prototype. Amplified EOG activity enters the analyzer and is passed through a narrow band-pass analog-filter amplifier which limits the response to the 2.0 to 3.75 Hz range, (-6 dB points). This frequency-response range results in optimal separation of true REM signals from extraneous activity (e.g., EEG activity detected by the EOG electrodes, slow eye movements, movement artifacts).

The output signal from the band-pass filter enters the EOG-transient-detector circuitry formed by the dual comparators and appended components. This circuit detects the occurrence of transient forms in the EOG signal which exceed a value equal to 250% of either the average positive or the average negative peak-voltage value of the EEG signal (averaging occurs continuously over approximately 15 sec). This transient detection is accomplished by driving the upper and lower voltage reference inputs of the dual EOG comparator with the rectified and filtered positive and negative components, respectively, of the output signal from the EEG-input amplifier. The EOG signal enters the comparator common input (after attenuation), where it is continuously compared to the upper and lower reference values. The attenuation factor is adjusted to permit the EOG signal at the comparator to just exceed the upper and lower values when a transient form in the unattenuated EOG output just reaches 250% of the averaged positive or negative EEG peak value. Thus, a trigger pulse is produced by the comparator each time such a transient occurs. Each such trigger pulse resets a 1.5 sec timer circuit which in turn supplies a 1.5 DC pulse to the following circuit (EOG-transient-only comparator). If EOG transients are detected with a frequency of one per 1.5 sec or greater, a continuous-level output results from the timer circuit for the duration of the train of transients and until 1.5 sec after the final trigger pulse.

The EOG-transient detector described above is quite effective in determining REMs, since these events usually occur sporadically and arise abruptly from the background activity. Since the circuit detects a relative increase in amplitude compared to the average of the preceding 10 sec of EEG (instead of utilizing fixed-voltage references), it is not necessary to readjust the circuit for individual differences in EEG amplitude. Thus, a change in background-activity level during the course of the sleep period causes the reference levels to automatically reset to proper relative values, thereby preventing false triggering of the comparator.

Although the EOG-transient detector successfully recognizes most true REMs, it will also be triggered by certain non-REM signals which may be present in the EOG channel. Electrode artifacts are one major source of such signals, and these are considered in the artifact-detection circuitry. Certain EEG events (vertex transients, K complexes) which occur frequently during stage 1 and 2 of sleep may also be recorded by the EOG-amplification system and detected as REMs because of their similarity in wave form and frequency components. This difficulty has been resolved by the remaining circuitry of the REM-detector circuit, which utilizes the following criteria: 1) High-amplitude EEG-transient events are recorded essentially simultaneously in the EEG and EOG channels because of their wide spatial distribution over the head. 2) True EOG events are recorded only in the EOG channel or are of insignificant amplitude in the central-to-occipital EEG channel because of their localized (frontal) origin. The final logic scheme permits an indication of the presence of a REM if 1) an EOG event is detected by the EOG-transient detector, and 2) no EEG event is detected by the EEG-transient detector within a time period extending from 1.4 sec before until 1.4 sec after the EOG event.

The EEG-transient detector is essentially identical to the EOG-transient detector described above, with the exception that the input signal is obtained from the input amplifier of the EEG analyzer and the threshold point is set to 350% of the average peak positive or negative EEG value. The output of this circuit is, thus, a 1.5 sec DC signal following each detected EEG-transient event. Output signals from the EOG-transient detector and the EEG-transient detector then enter the EOG-transient-only detector, which is composed of a single comparator followed by a 1.4 sec RC integration circuit. The comparator produces an output DC level whenever it receives an input signal from the EOG 1.5 sec timer alone. No output is possible while an input is received from the EEG timer. As long as the output of the comparator remains at zero, the RC circuit is held in a discharged state. When the comparator switches on, the RC circuit begins to charge with a time constant of 1.4 sec and continues to do so until fully charged or until discharged by the comparator's switching off.

The RC integration-circuit output is connected to the input of the following REM-indicator-output comparator, and the reference input of this comparator is biased at a voltage equal to the voltage output of the RC integration after charging for 1.4 sec. Therefore, if an EOG transient alone occurs, the 1.5 sec output pulse from the EOG timer results in a 1.5 sec output from the EOG-transient-only detector, which in turn is sufficient to charge the RC circuit in excess of the reference voltage on the final comparator, and an output pulse is produced. If an EEG transient occurs within 1.4 sec of the EOG transient, the pulse-output duration from the EOG-transient-only detector will be shortened (or completely eliminated if EOG and EEG transients occur exactly simultaneously), and the RC circuit will not charge to a voltage level sufficient to trigger the final REM-indicator-output comparator. Consequently, there is a pulse produced by the REM-indicator-output comparator only when an EOG transient occurs which is not accompanied by a similar EEG event.

If the disable relay (see discussion in Section 4, below) is closed (as drawn in Fig. 18, section 3), the output pulse from the REM indicator triggers a 30 sec resetting timer, which in turn supplies a DC level to the sleep-stage-output circuitry (Fig. 18, section 4). Since each REM output pulse resets the timer for 30 sec, a continuous output is produced by the timer if REMs are detected with a frequency exceeding one per 30 sec. Within the sleep-stage-output section, the REM-detector circuitry interacts with the outputs of the six EEG-analyzer voltage comparators to produce the final 7-stage output of the system. Outputs of the EEG stage 1 and stage 2 comparators enter an OR gate which thus produces an output when the EEG analyzer is in either stage 1 or 2. This signal enters an AND gate, together with the output of the EOG-transient detector, thereby making a REM detection impossible except when the EEG circuit indicates stage 1 or 2.

The output of the 30 sec REM-timer circuit enters one input of an AND gate whose other input is the inverted output of the AWAKE comparator. This AND gate will consequently produce a true output only when the 30 sec REM timer is activated and the output of the AWAKE comparator is not present. A true output from the AND gate results in an output indication of stage REM and also causes suppression of all other stage outputs (1 through 0). Thus, once the 30 sec REM timer is triggered, the output will remain in stage REM until the timer resets, unless the AWAKE comparator is activated, and in this case the output switches to stage awake.

4. Artifact-Detection Circuitry (See Fig. 18, section 2; Fig. 19, section 2)

a. General. Although the EEG and EOG acquisition methods have been designed to minimize the occurrence of artifactual signals, it has not yet been possible to completely eliminate them. The majority of artifactual signals seen during a number of all-night studies using the electrode-cap and preamplifier assemblies have been directly related to major bodily movements of the subject. While free movement of the head itself causes almost no problems, when the subject is reclining such movements result in changing forces exerted directly on the recording electrodes at the points where contact is made with the bed. Such disturbances of the scalp-electrolyte and electrolyte-electrode interfaces result in changes in the electrode-junction potentials and alteration of other characteristics of the electrodes, which are manifested as artifactual signals in the recorded data.

The purpose of the artifact-detection circuitry is to prevent signals with a high probability of artifactual contamination from influencing the sleep-stage-determination systems. This is accomplished by disabling the EEG and EOG analysis sections during and for 4 sec following either of these events: 1) excessive EEG amplitude, or 2) head movements in excess of tolerable limits (from accelerometer on recording-cap preamplifier).

b. Theory of Operation and Construction of Prototype

1). Excessive-EEG-Amplitude Detector. Disturbances of the scalp-electrode interface which occur with rapid movement of the head and/or changing forces on the electrodes usually result in low-frequency, irregular, often high-amplitude artifactual signals in the EEG channel. If such events occur when the subject is awake or in stage 1, 2, or REM sleep, the EEG-analysis section, unless disabled, will consider the high-amplitude, low-frequency artifactual signal to be delta activity, and if persistent for several seconds will deliver a false indication of a lower sleep stage (e.g., stage 3 or 4). If not persistent, a transient descent of only one stage may result (e.g., from awake to stage 1 and back), producing a false indication of drowsiness.

Because of the abrupt onset of this type of artifactual signal, when such an event occurs in the EOG channel a transient output is produced by the narrow band-pass filter (1-3 Hz) which, if high enough in amplitude, will be detected by the EOG-transient detector. Unless a similar event is detected simultaneously in the EEG channel, a false indication of a REM will then be produced. If the EEG analyzer was indicating stage 1 or 2 at the time, the analyzer final output would switch to stage REM, unless disabled.

The excessive-amplitude detector minimizes the occurrence of such false indications by disabling the EEG-analyzer section and the REM-indicator-output section during and for a 4 sec period following the occurrence of an excessively high amplitude EEG signal, thus preventing a change in the sleep-stage-output section as a result of this period of artifact.

The EEG signal is obtained after the first stage of amplification within the EEG-analysis section and enters the artifact-detection circuitry (Fig. 18, section 2). The signal next enters a dual comparator which produces a trigger pulse if either the positive or negative phase of the EEG-channel voltage exceeds a value of 600% (the same relative amplitude scale used in the EEG-analysis section is used here; see Section V, B, above), which is considered to be in excess of the usual physiological range. The resultant trigger pulse starts the 4 sec artifact-detection timer which in turn operates the disable relay for the 4 sec period. If the timer receives trigger pulses at a rate equal to or exceeding one per 4 sec, the disable relay will remain activated continuously.

When the disable relay is activated, the EEG-analysis section is effectively disabled by disconnection of the pulse-train output of the positive and negative pulse generators from the input to the integration circuit. The discharge pathway for the integration capacitor is also removed during this time, and consequently the output of the integrator remains unchanged for the duration of the disabled period.

Activation of the disable relay also results in disconnection of the REM-output indicator from the REM-timer input. Consequently, a REM detected during the 4 sec (or longer) period has no influence on the final sleep-stage-determination section (Fig. 18, section 4).

2). Head-Movement Detector. The accelerometer contained in the preamplifier and attached to the recording cap serves as another means for detecting periods when artifactual contamination is highly probable. Head movement results in the production of an output voltage from the accelerometer which is roughly proportional to the rapidity of the motion; thus, a high-voltage output from this device is more likely to be associated with movement artifact in the EEG and EOG channels.

Output of the dual accelerometer enters the accelerometer amplifier filter (bandwidth, 0.1-10 Hz) in the artifact-detection section of the analyzer (Fig. 18, section 2), which provides a gain of approximately 500. The amplified and filtered activity enters a dual-comparator circuit which produces a trigger pulse if either the positive or negative phase of the input signal exceeds the fixed reference values. The reference values were determined experimentally during preliminary testing such that the output produced by the accelerometer when a subject turned over while reclining in bed was sufficient to trigger the comparator.

When triggered, the accelerometer comparator in turn resets the 4 sec artifact-detection timer, and the disable relay is consequently activated for the duration of, and for 4 sec following, the movement. Subsequent testing under controlled conditions has indicated that such movements represent changes in acceleration of approximately 0.2 g in either the vertical or lateral axis. The following table indicates the trigger points at different frequencies when a sinusoidally changing force was utilized to activate the accelerometer.

Vertical Axis Frequency	Acceleration Value Needed to Trigger Artifact Detector
3 Hz	0.11 g*
4 Hz	0.12 g
5 Hz	0.07 g
10 Hz	1.0 g
20 Hz	0.16-0.18 g
30 Hz	0.16-0.18 g
60 Hz	0.35 g

*g = acceleration due to earth's gravity.

Lateral Axis Frequency	Acceleration Value Needed to Trigger Artifact Detector
2.4 Hz	0.075 g
3 Hz	0.065 g
4 Hz	0.07 g
5 Hz	0.05 g
10 Hz	0.1 g
20 Hz	0.19 g
30 Hz	0.28 g
40 Hz	0.32 g
60 Hz	0.63 g

VI. ANALYZER OUTPUT TO TELEMETRY LINE (See Fig. 18, section 4, and Fig. 19, section 4)

The outputs of the six sleep-stage comparators and the REM indicator are combined in the output section of the analysis circuitry (Fig. 18, section 4) by an analog adder which provides the single output line to the telemetry link. The input resistors of the adder circuit (Fig. 19, section 4) are selected to provide the desired output characteristics, as follows:

Awake	=	0.929 V
Stage 1	=	1.561 V
REM	=	2.194 V
Stage 2	=	2.826 V
Stage 3	=	3.459 V
Stage 4	=	4.091 V
Stage 0	=	4.723 V

The output is sampled by the telemetry transmitter at a suitable rate (at least one 3-bit sample per 10 sec), and the voltage is reconstructed at the remote (ground-based) monitoring station where it is applied to the input of the display console. For laboratory testing where no telemetry link is needed, the output of the sleep-analysis section may be connected directly to the input of the display-console circuitry (described below).

VII. DISPLAY CONSOLE

A. General Description

This unit is located at the ground-based monitoring site and accepts the 7-level voltage input from the telemetry system. Three simultaneous display modes are provided by the unit:

1. A visible indication of the current sleep state of the subject
2. A cumulative, numerical display (in minutes) of the total amount of time which has been spent in each of the stages
3. A stepwise, graphic recording of subject sleep stage versus time

B. Circuit Description (See Fig. 21)

As indicated in Fig. 21, the voltage level from the telemetry line (which is proportional to sleep stage) enters the display console where it is presented to the common inputs of a series of seven comparator circuits, each corresponding to one of the predefined stages. The reference levels of each comparator are fixed such that the comparator will respond only if the input voltage is within a narrow range above or below the specified voltage value for the particular stage (see table in Section VI, above).

The output of each comparator is normally held at a positive value. When the input voltage falls within the range of a particular comparator, its output is switched to zero, or ground, potential. Since the output of the sleep analyzer, and consequently the output of the telemetry link, is restricted at all times to one of the seven specified levels, one comparator will always be switched "on" (zero volts output).

Each stage-detector comparator connects to a relay-driving circuit composed of two 2N3646 transistors and associated components, Q_1 and Q_2 (see Fig. 21). The first transistor, Q_1, of the pair is normally held in the "on" condition, since the positive output of the comparator circuit is connected to its base through a 1.2 KΩ resistor. Since the second 2N3646, Q_2, is driven from the collector of the first, it is normally held in the "off" condition, and consequently the relay in series with the collector of the Q_2 is normally inactivated.

When one of the stage comparators switches to the "on" condition, Q_1 is immediately switched "off." However, because of the 500 μF capacitor located between the collector and ground of Q_1, Q_2 does not switch "on" immediately but does so after a delay time (capacitor charge time) of approximately 0.5 sec. If the stage comparator reverts to the "off" condition, the relay is immediately inactivated, since Q_1 goes "on," immediately shorting the 500 μF capacitor to ground, thereby turning Q_2 "off." This 0.5 sec on-time delay is necessary to compensate for the inertial "coasting" effect when the elapsed-time indicator is turned off.

Consequently, at any given time, one of the relay circuits will be found "on," thus showing the current sleep stage indicated by the remotely located analyzer. When in the "on" condition, each double-pole relay activates its corresponding panel lamp (Drake 5131-072) to indicate the current stage of sleep and simultaneously turns on a cumulative-time indicator clock (TY meter 131-24H). Each elapsed-time indicator thus keeps a cumulative record of the amount of time the corresponding panel lamp is illuminated, and this value is equivalent to the total amount of time occupied by that particular stage of sleep.

The input telemetry signal to the display console, since it is an analog voltage proportional to sleep stage, may also be utilized, after suitable amplification, to drive the vertical axis of a strip-chart recorder to obtain a graphic profile of sleep stage versus time. As indicated in Fig. 21, initial amplification is provided by the Fairchild 741 operational amplifier and final amplification by the differential configuration consisting of two 2N1304 and two 2N456 transistors. This circuit is sufficient to drive the pens of the M. F. E. model M-2 recorder, which runs at a speed of approximately 7 in./hr.

VIII. TOTAL SYSTEM EVALUATION

A. General

Fig. 22 shows the complete prototype operational system for automatic sleep monitoring. The items on the left side are those intended for location on board the spacecraft — the recording cap, the preamplifier, the control-panel assembly (with contained tape recorder), and the automatic analyzer — while the ground-based display console is shown on the right.

B. Functional Testing

The testing format outlined in Table I permits a reasonably thorough evaluation of the sleep-monitoring system to be made using commercial test equipment. Known input conditions are supplied for the preamplifier (in place of the recording cap), and the telemetry-output condition is monitored at specified intervals following the change in input values.

The following functions are tested (refer to Table I).

1. EEG Analyzer and Output Comparators, Preamplifier, and Final Preamplifier

a. A 50 μV peak-to-peak sine-wave input signal is supplied to the EEG inputs of the preamplifier. Proper setting of the input potentiometer (25 μV = 60%) of the automatic analyzer results in crossing of amplitude levels 1 and 2, but not 3, within the EEG-analyzer section (Fig. 18, section 1). Selected frequency values are utilized to assure proper recognition of stage awake, 1, 2, 3, 4, and 0.

b. Proper function of level 3 (Fig. 18, section 1) is tested by applying a signal equivalent to 150%.

2. Excessive-Amplitude Comparator and Artifact-Disable Circuit

a. An input signal of 5.3 Hz, crossing levels 1 and 2, is initially utilized to obtain the awake state as observed at the telemetry output.

The input amplitude is abruptly changed to a value in excess of 600%. Proper functioning of the excessive-amplitude comparator and artifact-disable circuit is indicated if the awake state is maintained at the end of the 60 sec observation period. Malfunction of these circuits would allow the output to fall to stage 3, since levels 1, 2, and 3 of the EEG-analysis system are exceeded by the input signal.

3. EEG- and EOG-Transient Detection

a. A 200 μV peak-to-peak 2.5 Hz signal (simulated REM) is applied to the EOG input while the EEG section is maintained in the awake state by a level 1, 2 signal of 5.3 Hz applied to the EEG input. Proper function is indicated by the persistence of the awake state throughout the 60 sec observation period.

b. The sequence outlined in a. is repeated with the EEG input changed to 4.2 Hz to maintain the EEG section in stage 1. Proper function is indicated by immediate transition to stage REM,. which is held for 30 sec, then a return to stage 1.

c. The sequence outlined in b. is repeated while the EEG state is maintained in stage 2 by a 3.0 Hz EEG input signal. Proper function is a 30 sec REM indication, with a return to stage 2.

d. The sequence outlined in a. is repeated while the EEG state is held in stage 3 with a 2.2 Hz signal. Proper function is a continuous indication of stage 3.

e. Function of the EEG-transient detector is tested by an abrupt increase in the EEG input amplitude activity simultaneous with the EOG transient. Proper function is a change in output state to stage 3, with no intervening REM period.

4. Accelerometer Comparator and Artifact-Disable Circuitry

The awake state is attained initially with a 6.0 Hz signal crossing levels 1 and 2 in the EEG-analysis section. Motion of the preamplifier is initiated (2 Hz with 6" excursions) simultaneous with cessation of the EEG input signal. Proper function is maintenance of the awake state for the duration of the preamplification period. Motion of the preamplifier is stopped, and stage 0 should be indicated within 60 sec.

C. Operational Testing

During the course of the contract period, a considerable number of tests were carried out to evaluate specific aspects of the monitoring system, including approximately 100 all-night sleep studies. These studies have led to a high degree of confidence concerning the ability of the system to perform adequately under the proposed space-flight conditions.

The comfort of the current-version recording cap has been thoroughly proven, as has its ability to acquire the bioelectrical signals throughout 6 to 12 hr recording sessions. Preparation procedures and time requirements have been reduced to 2-3 min under laboratory conditions, and the automatic electrode-checking device has proven to be a satisfactory indication that proper electrical contact has been accomplished.

An example of an all-night sleep profile, as produced by the graphic recorder of the display console, is shown in Fig. 23. Comparisons have been made between the analyzer output and the results of expert human visual interpretation of the same data. Side-by-side observation of the profiles (e.g., Fig. 24) generally shows good agreement between the two methods, with most discrepancies being of only one stage. When a point-by-point statistical comparison is made between such plots of all-night sleep records (i.e., determining the percentage of epochs which the analyzer scores exactly the same as the human observer), the overall agreement ranges between 70 and 80% when each stage is given equal weight. The result of one such example is shown in Table II. While the overall agreement was approximately 70%, it may be seen that the greatest difficulty was presented by stage REM, where the analyzer agreed only 42% of the time. Best results were noted with stage 2 (91%) and awake (80%).

Some improvement in performance may be gained by further "smoothing" the data output of the analyzer. Thus, since the analyzer must detect at least one rapid-eye-movement event per 30 sec to maintain the REM state, as illustrated in Fig. 23, most REM periods show considerable functuation between stage 1, REM, and stage 2. The human evaluation of these same periods would show a much higher percentage of the time spent in REM and fewer fluctuations into stage 1 and 2, since one REM per 30 sec is not an essential requirement for the human. It is believed that the present somewhat conservative behavior of the analyzer with respect to stage REM is more satisfactory than the alternative, which is relaxing the requirement for one rapid eye movement per 30 sec. A modification, for example, which resulted in a continuous indication of stage REM with one REM per 60 sec would increase the reliability in the ideal situation. However, because of constant possibility of unsuspected artifacts, particularly under the unknown circumstances associated with sleep recording under weightless conditions, the present scheme will offer the investigator a more "fine-grained" output from which to draw his conclusions.

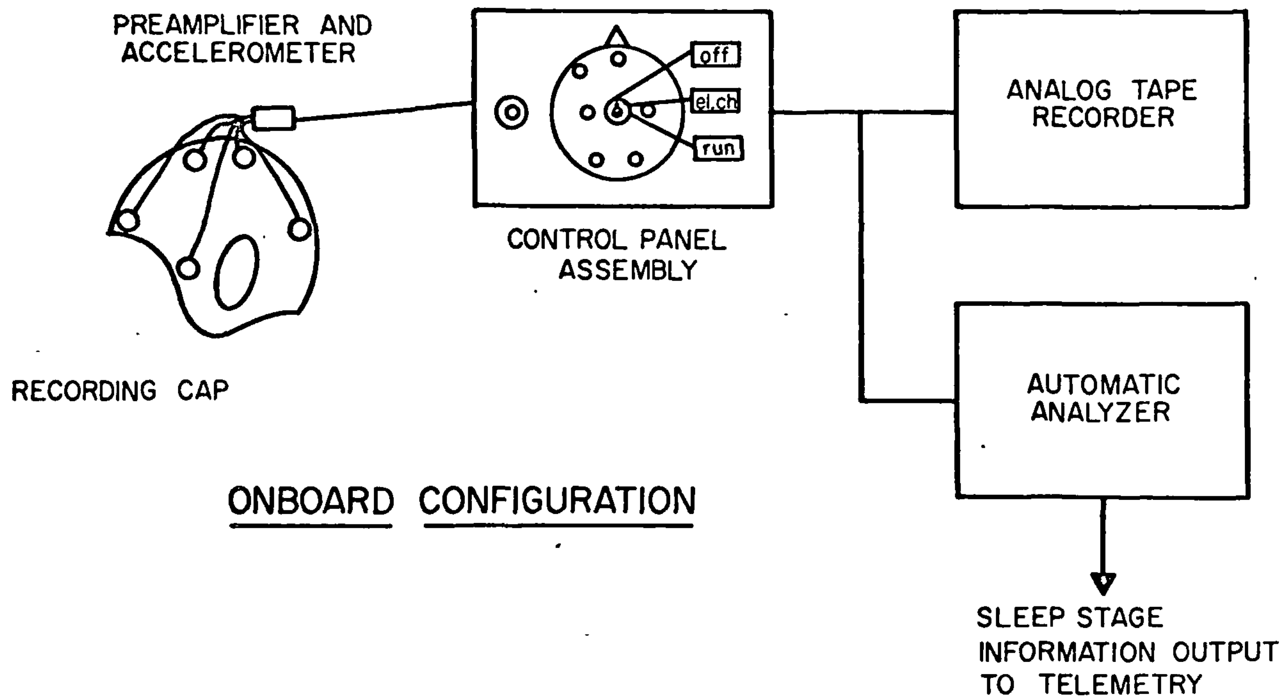
NOTES

1. Silastic S-5370 RTV silicone-rubber foam base, Dow Corning Corp., Midland, Mich.
2. Silastic S-5370 Catalyst, Dow Corning Corp., Midland, Mich.
3. Gem Manual Hole Punch, McGill M. P. Co., Marengo, Ill.
4. Caltron Industries, 2015 Second St., Berkeley, Calif.; type #3003-028029, 1 cond., 29 AWG, silicone insulated.
5. Ersin multicore five-core silver alloy solder, Multicore Solders Ltd., Hempstead, Herefordshire, England.
6. G.E. RTV 112 White Silicone Rubber Adhesive, General Electric Co., Waterford, N.Y.
7. Silastic 1200 Primer, Dow Corning Corp., Midland, Mich.
8. Silastic-A RTV mold-making rubber base, Dow Corning Corp., Midland, Mich.
9. Silastic-A Catalyst #4, Dow Corning Corp., Midland, Mich.
10. Vyna-Kote Red Liquid Vinyl, Spectra-Strip Wire and Cable Corp., P. O. Box 415, Garden Grove, Calif.
11. Vyna-Kote Clear Liquid Vinyl, Spectra-Strip Wire and Cable Corp., P. O. Box 415, Garden Grove, Calif.
12. A suitable electrolyte solution contains the following: NaCl, 1.36 g; KCl, 0.08 g; $MgCl_2 \cdot 6H_2O$, 0.04 g; $NaH_2PO_4 \cdot H_2O$, 0.3 g; KH_2PO_4, 0.002 g; Natrosol-250, 2.5 g; polyvinylpyrrolidone-K90, 2.0 g; Zephiran chloride concentrate, 2 ml; H_2O to make 100 cc total solution volume.
13. Some loss of fluid content can occur with the passage of time because of the slight permeability of the vinyl coat to water vapor, particularly if the completed electrodes are stored in a low-humidity environment. This effect may be eliminated by storing a number of completed electrodes or electrode assemblies in sealed polyethylene bags, or by utilizing a coating material with lower water-vapor permeability.
14. No. 260-3816, Microdot Inc., 220 Pasadena Ave., South Pasadena, Calif. 91030.

ACKNOWLEDGMENTS

Work completed during the contract period was made possible by the collaboration of a number of members of the Section of Neurophysiology, Baylor College of Medicine, and the Neurophysiology Department, The Methodist Hospital, Houston, Texas. Mr. Kenneth Nevill and Mr. Carl E. Hillman, Jr., participated extensively in the design and construction of the prototype system; Mrs. Eileen Turner constructed the recording caps; Miss Sandra Hagan was responsible for the illustrations and assisted during many of the experimental procedures; Mrs. Marilyn Ekeroot and Mrs. Adrienne Jacobson were responsible for the documentation and preparation of the required reports.

FIGURES AND TABLES



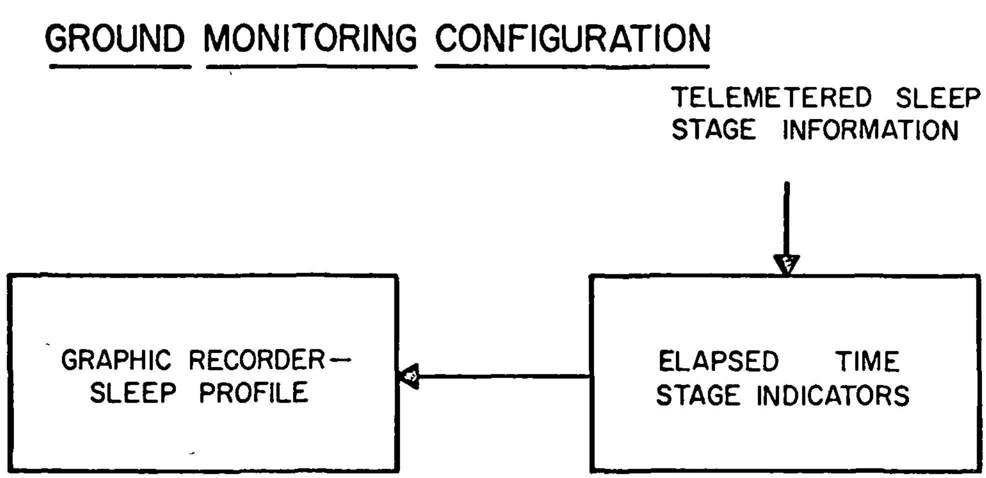


FIG. I
BLOCK DIAGRAM OF SLEEP MONITORING SYSTEM

Fig. 2

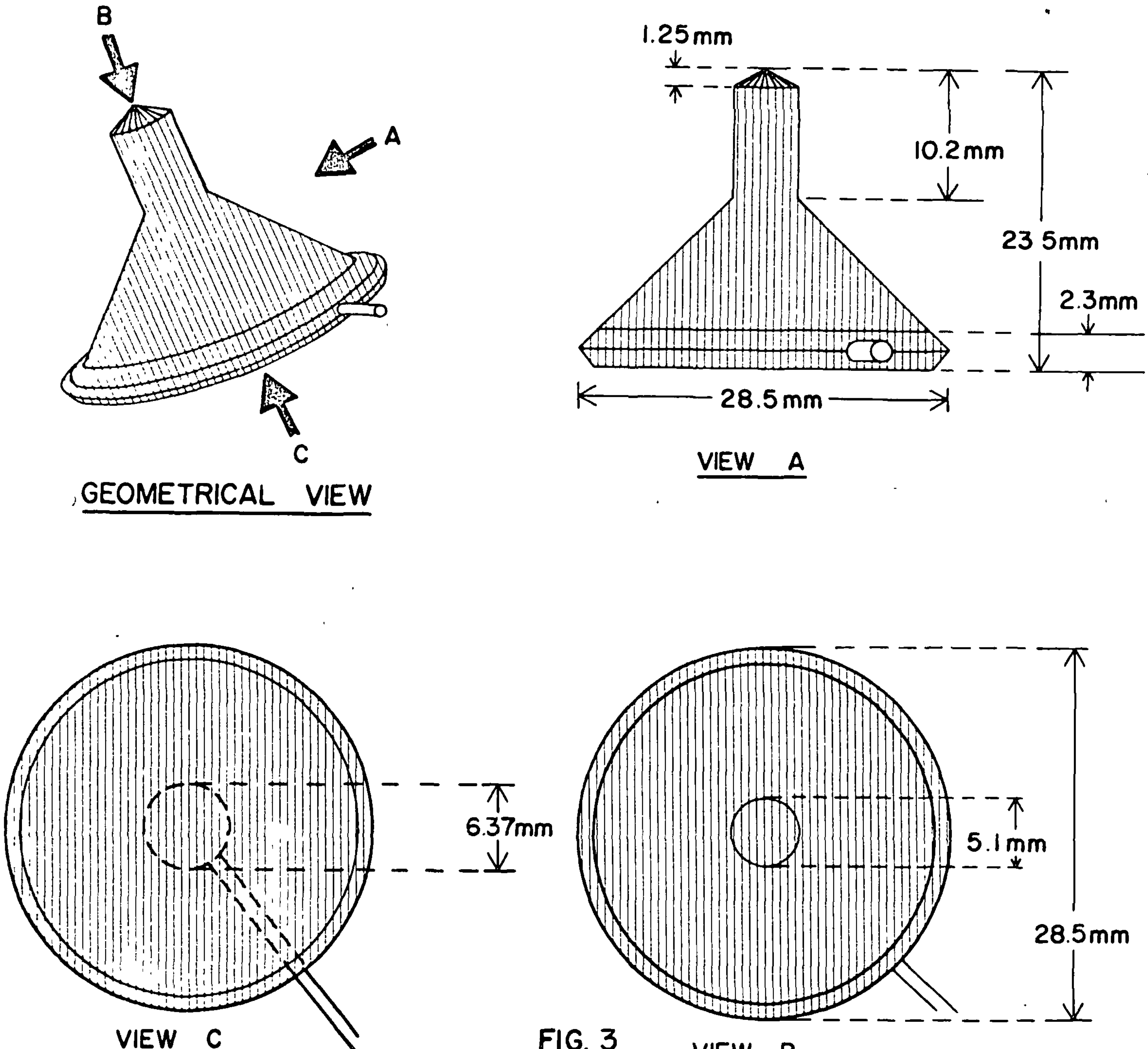
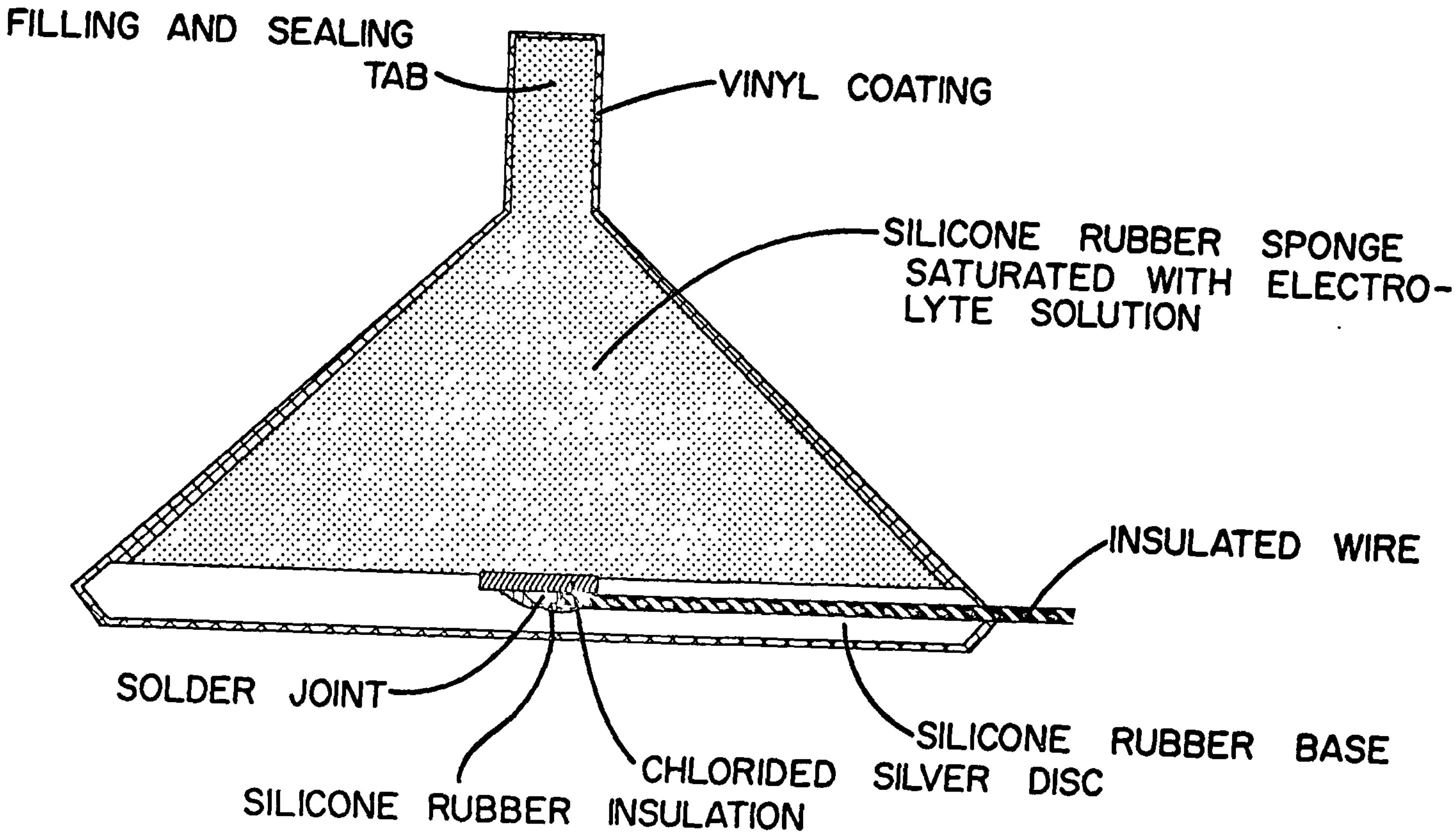

B
A
C
GEOMETRICAL VIEW
1.25mm
10.2mm
23.5mm
2.3mm
28.5mm
VIEW A
6.37mm
VIEW C
5.1mm
28.5mm
VIEW B

FIG. 3



CROSS SECTION OF PREFILLED SPONGE ELECTRODE

FIG. 4

RECORDING CAP PATTERN

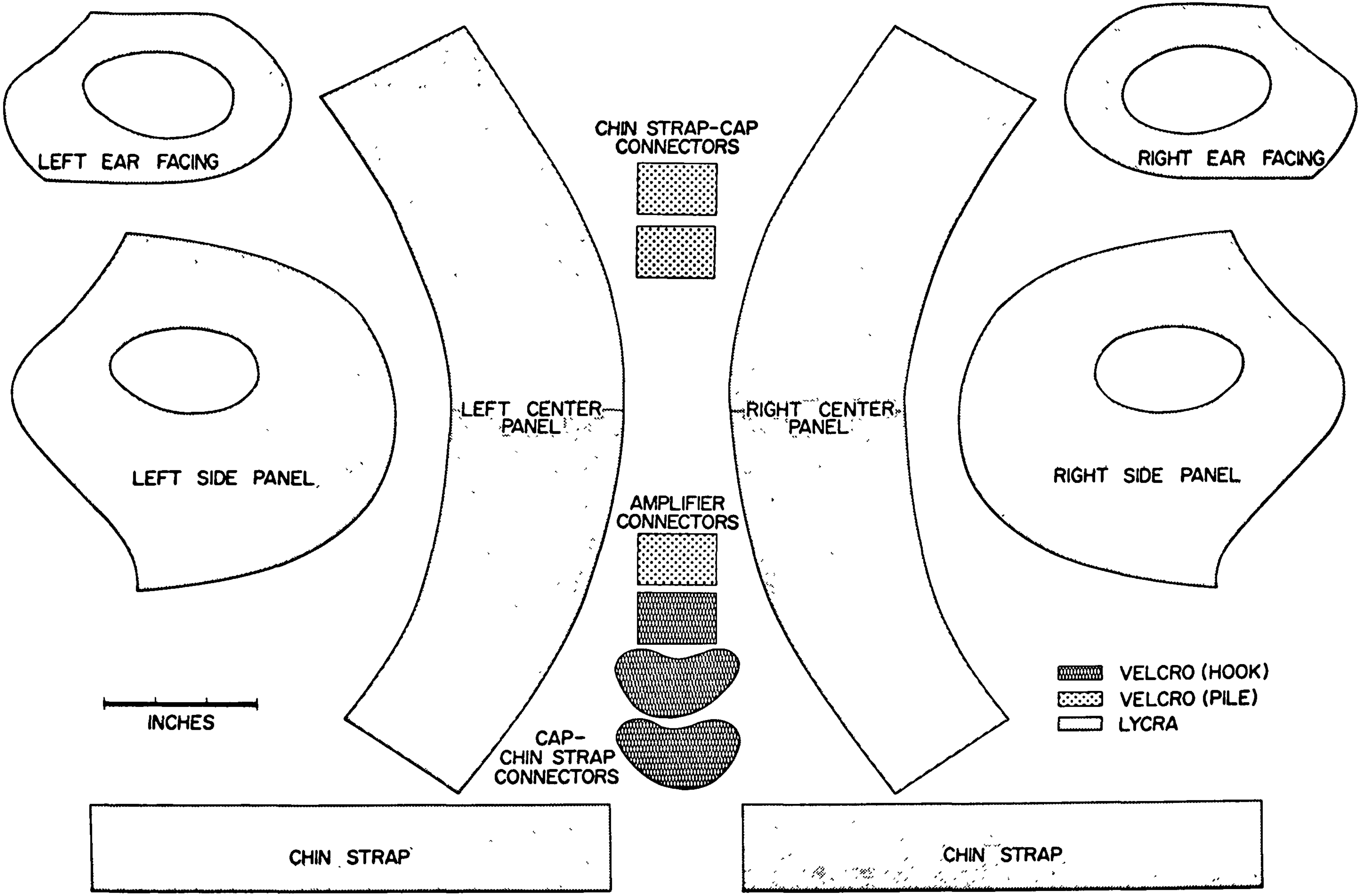


FIG. 5

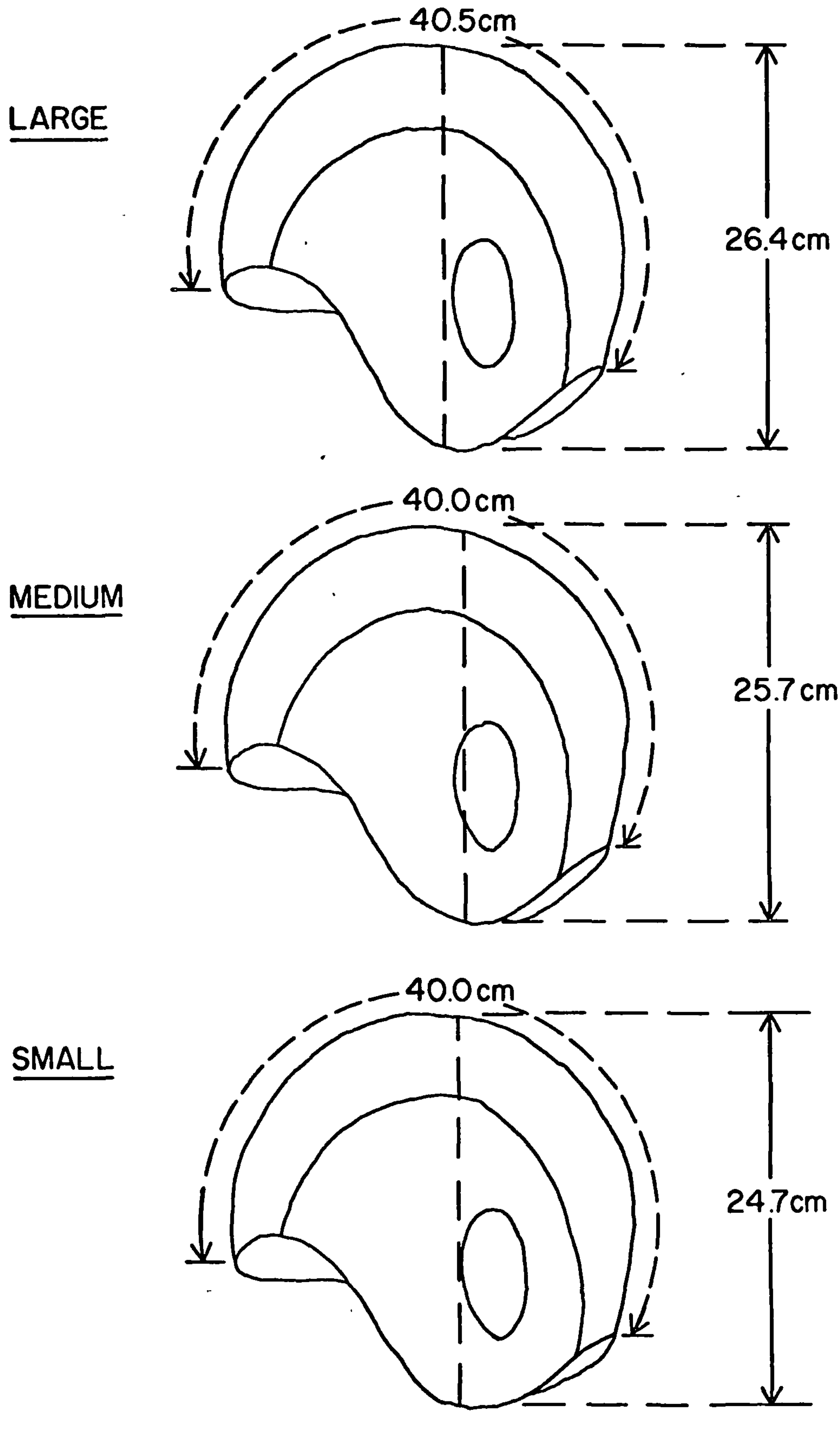


FIG. 6 – COMPARISON OF CAP SIZES

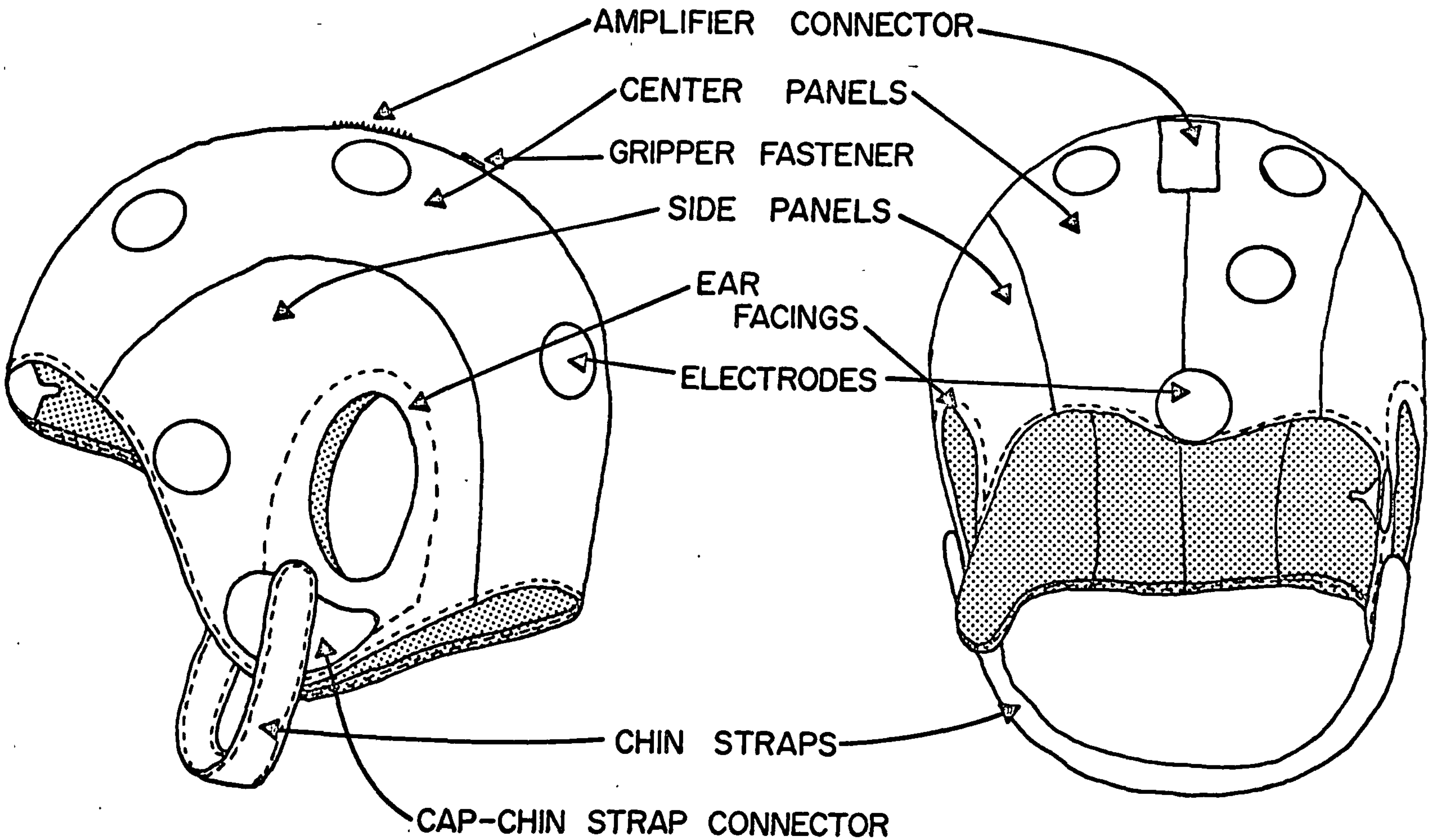


FIG. 7
CAP CONSTRUCTION

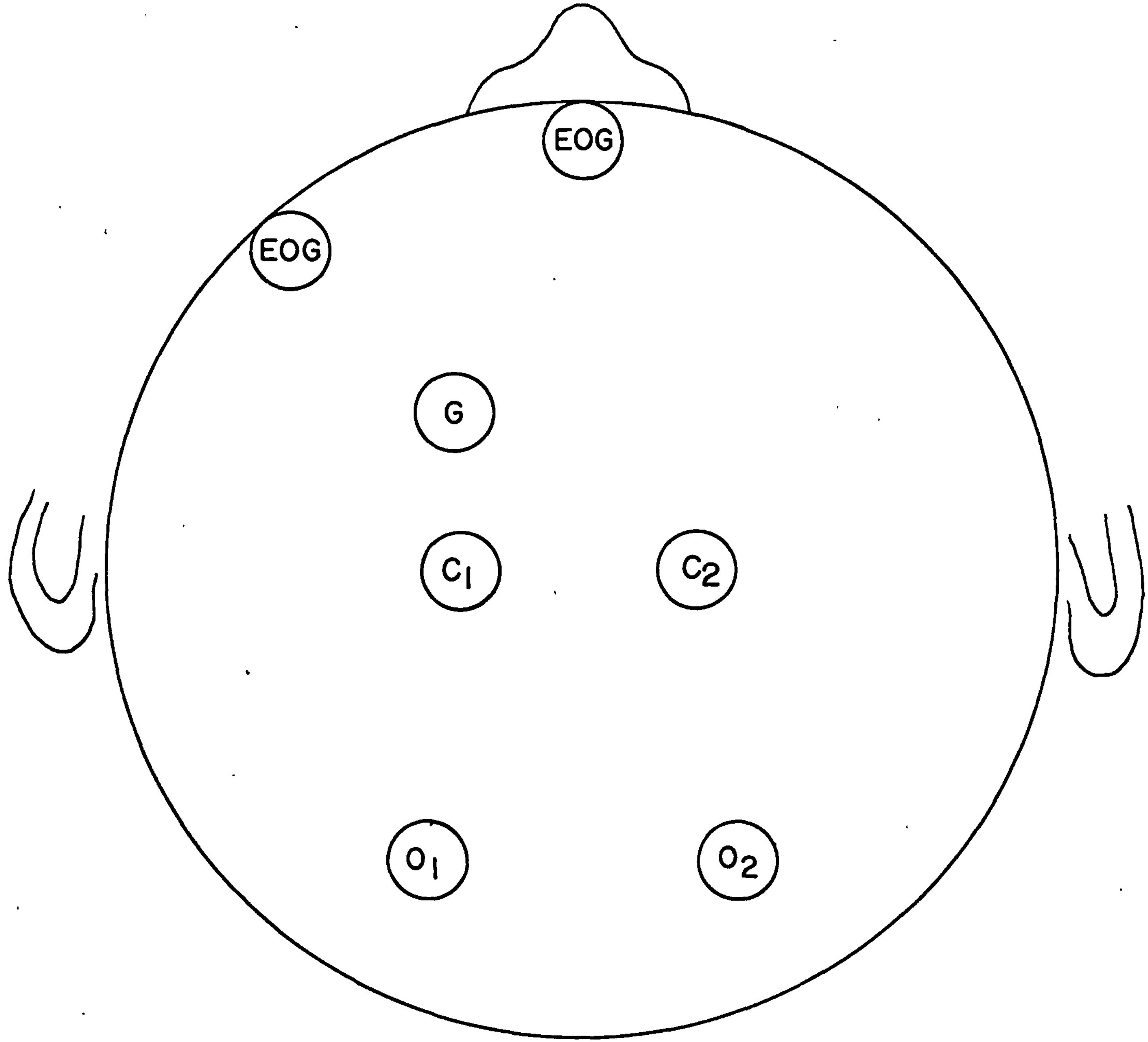


FIG. 8 — STANDARD CAP ELECTRODE POSITIONS

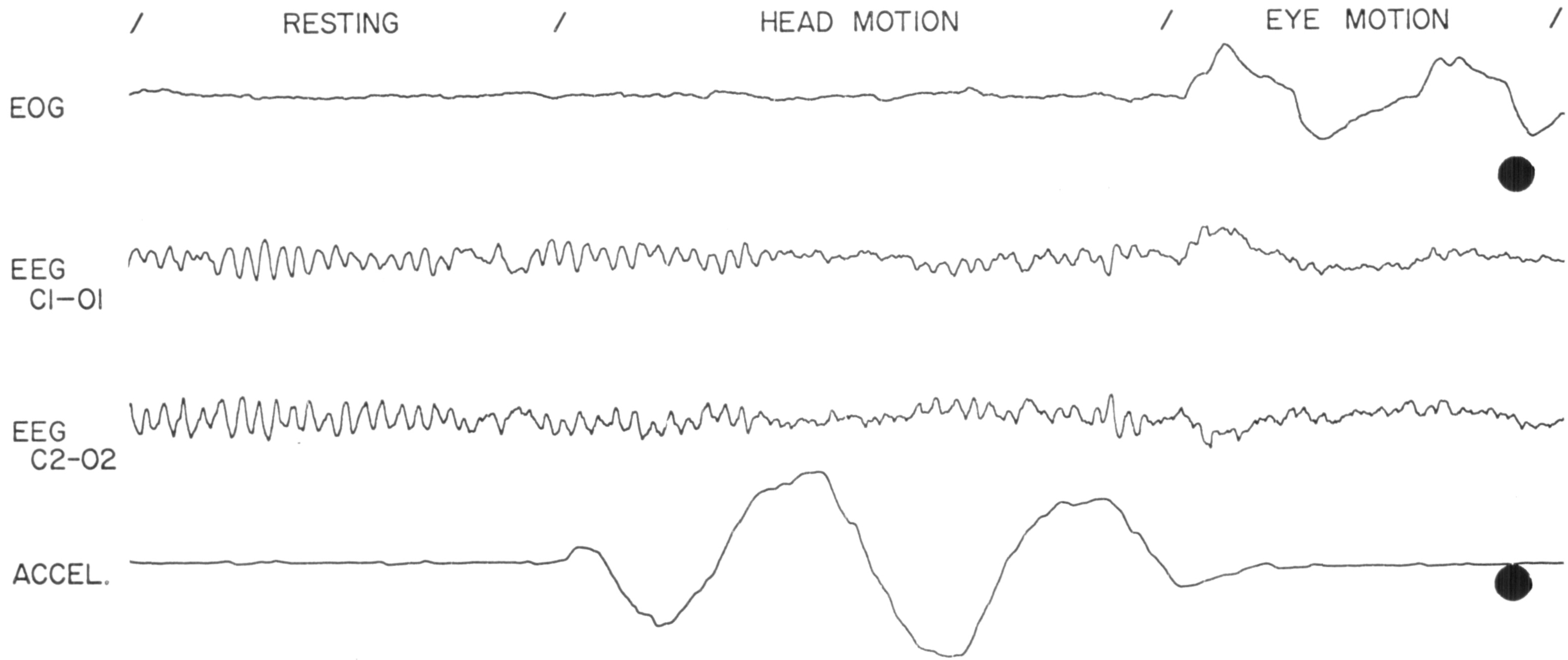


FIG. 9—EEG, EOG, ACCELEROMETER FROM STANDARD ELECTRODE CAPS

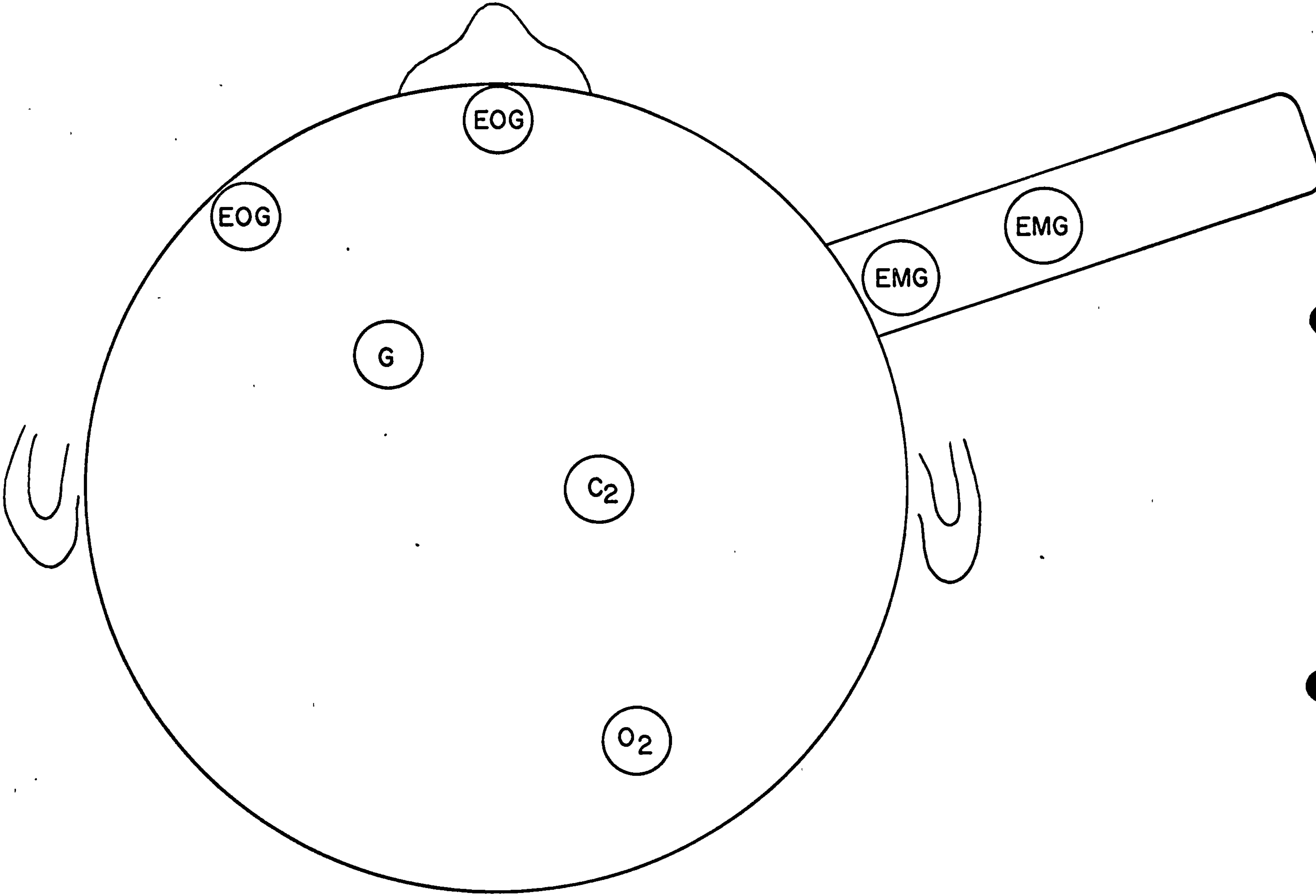


FIG. 10 - CHIN STRAP ELECTRODE POSITIONS

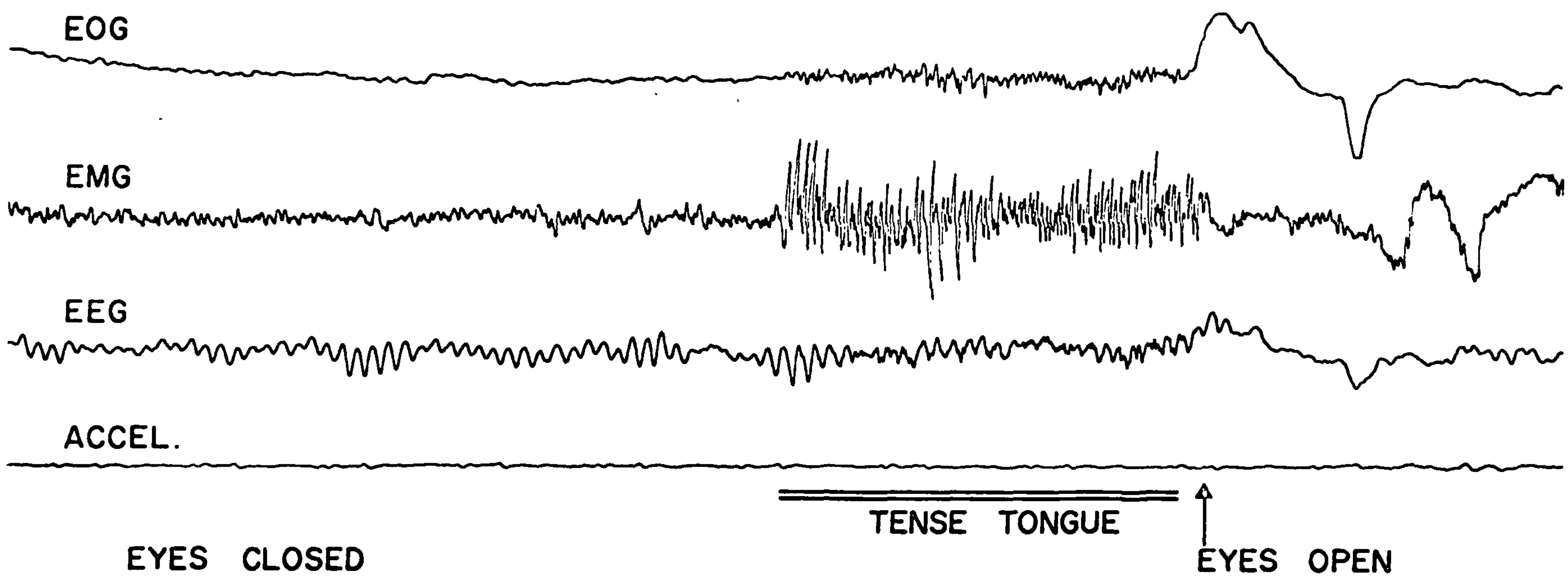


FIG. 11

PREPARATION OF ELECTRODE FOR USE

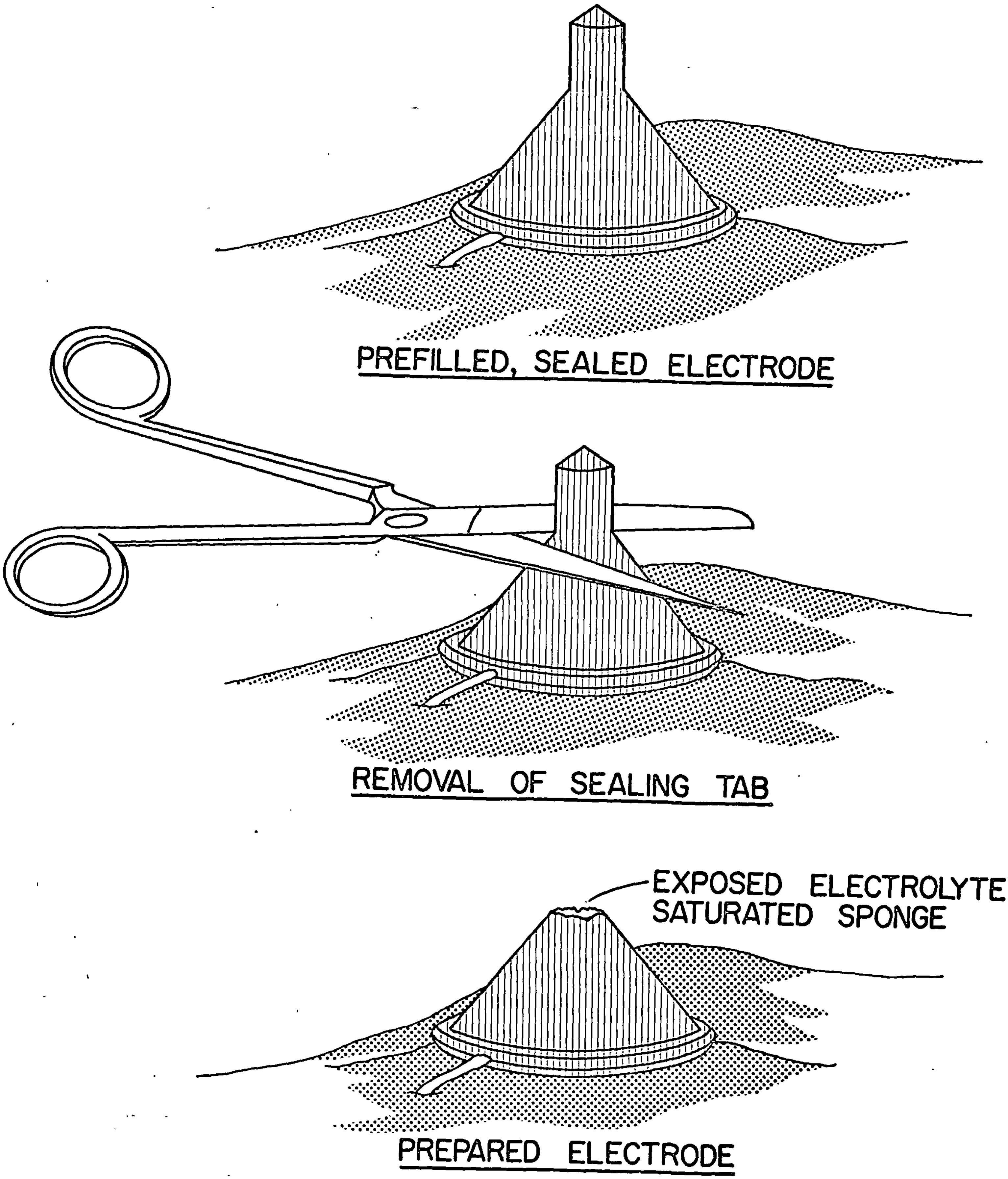


FIG. 12

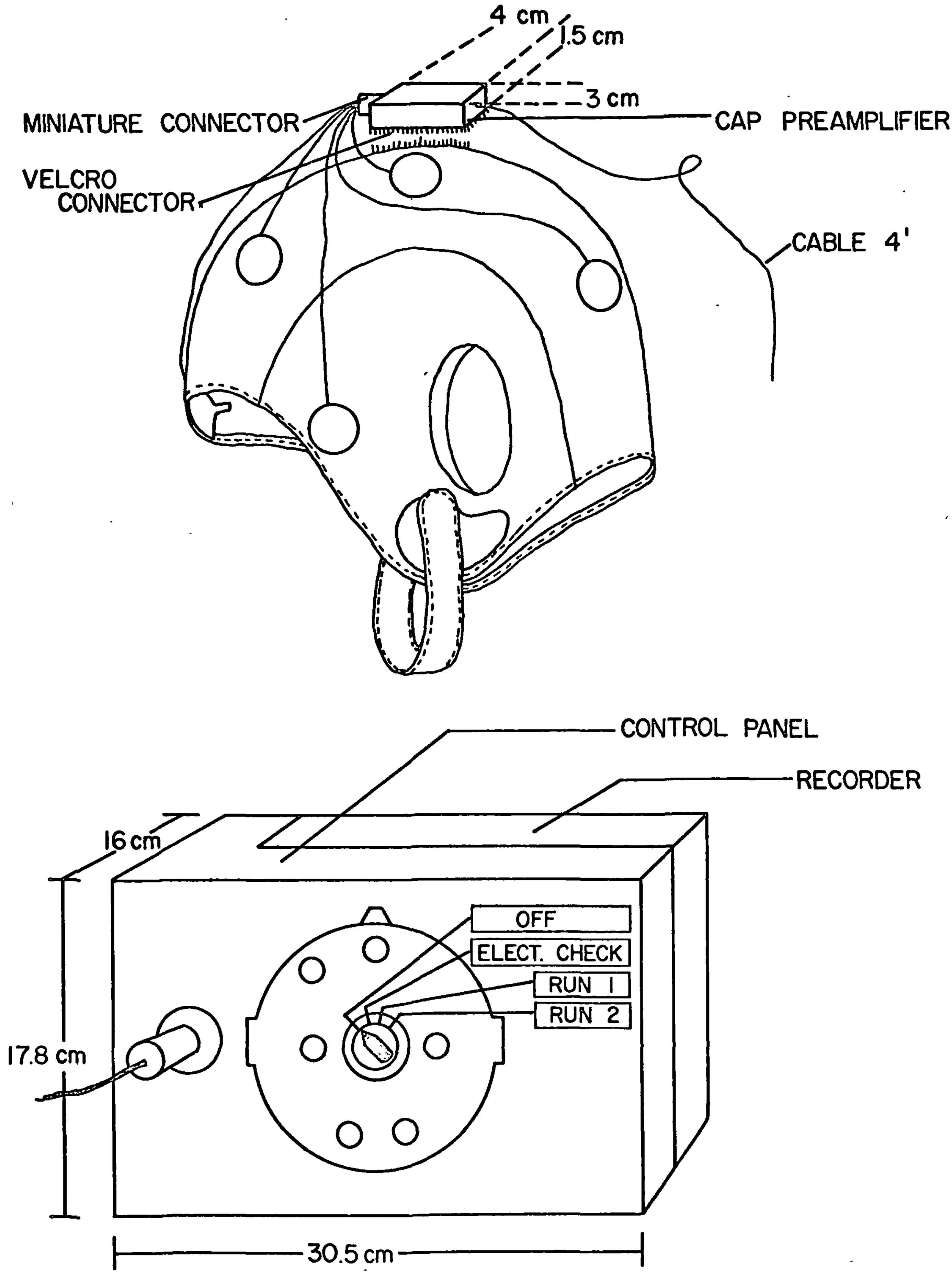

4 cm
1.5 cm
3 cm
MINIATURE CONNECTOR
CAP PREAMPLIFIER
VELCRO CONNECTOR
CABLE 4'
CONTROL PANEL
RECORDER
16 cm
OFF
ELECT. CHECK
RUN 1
RUN 2
17.8 cm
30.5 cm

FIG. 13

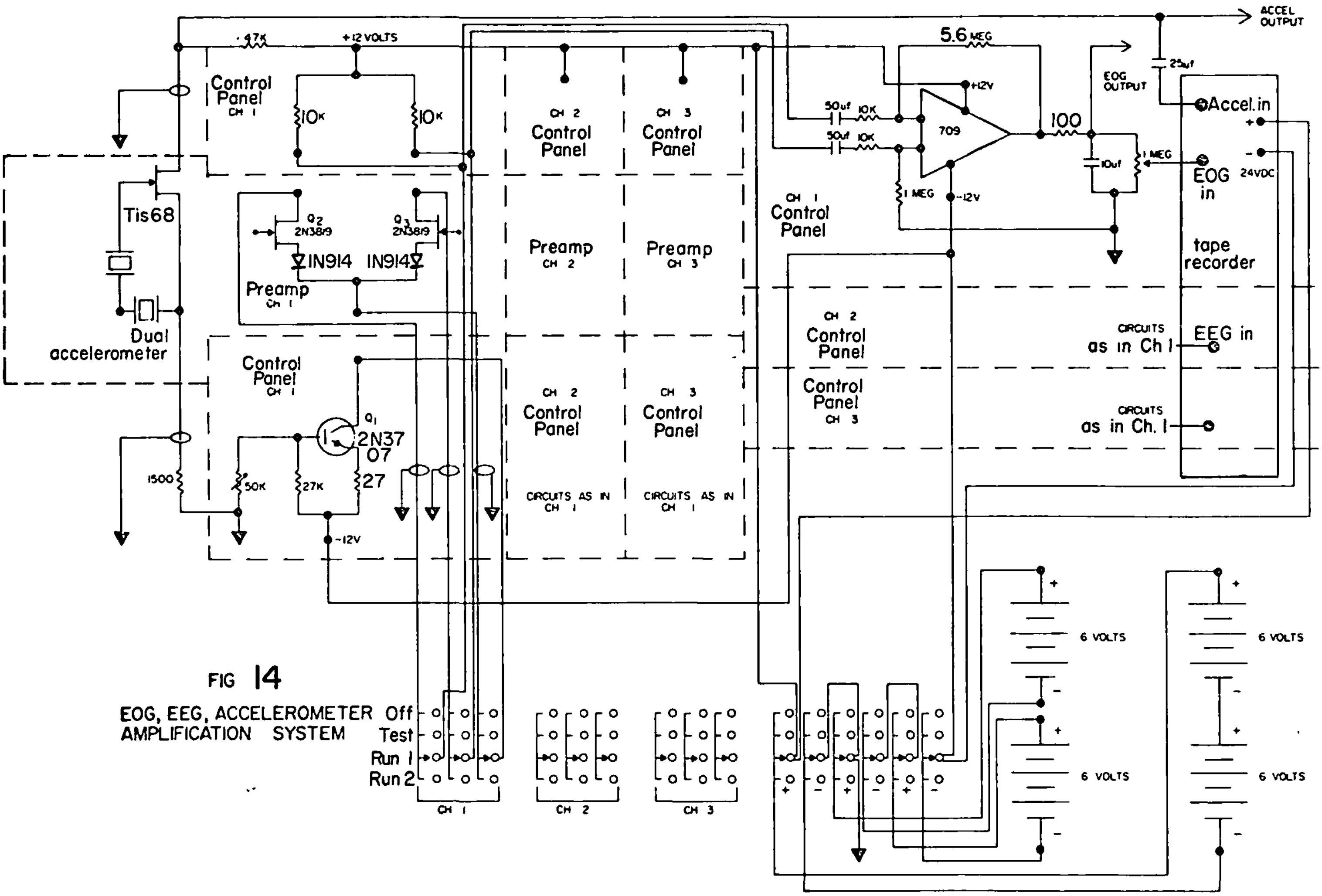


FIG 14

EOG, EEG, ACCELEROMETER AMPLIFICATION SYSTEM

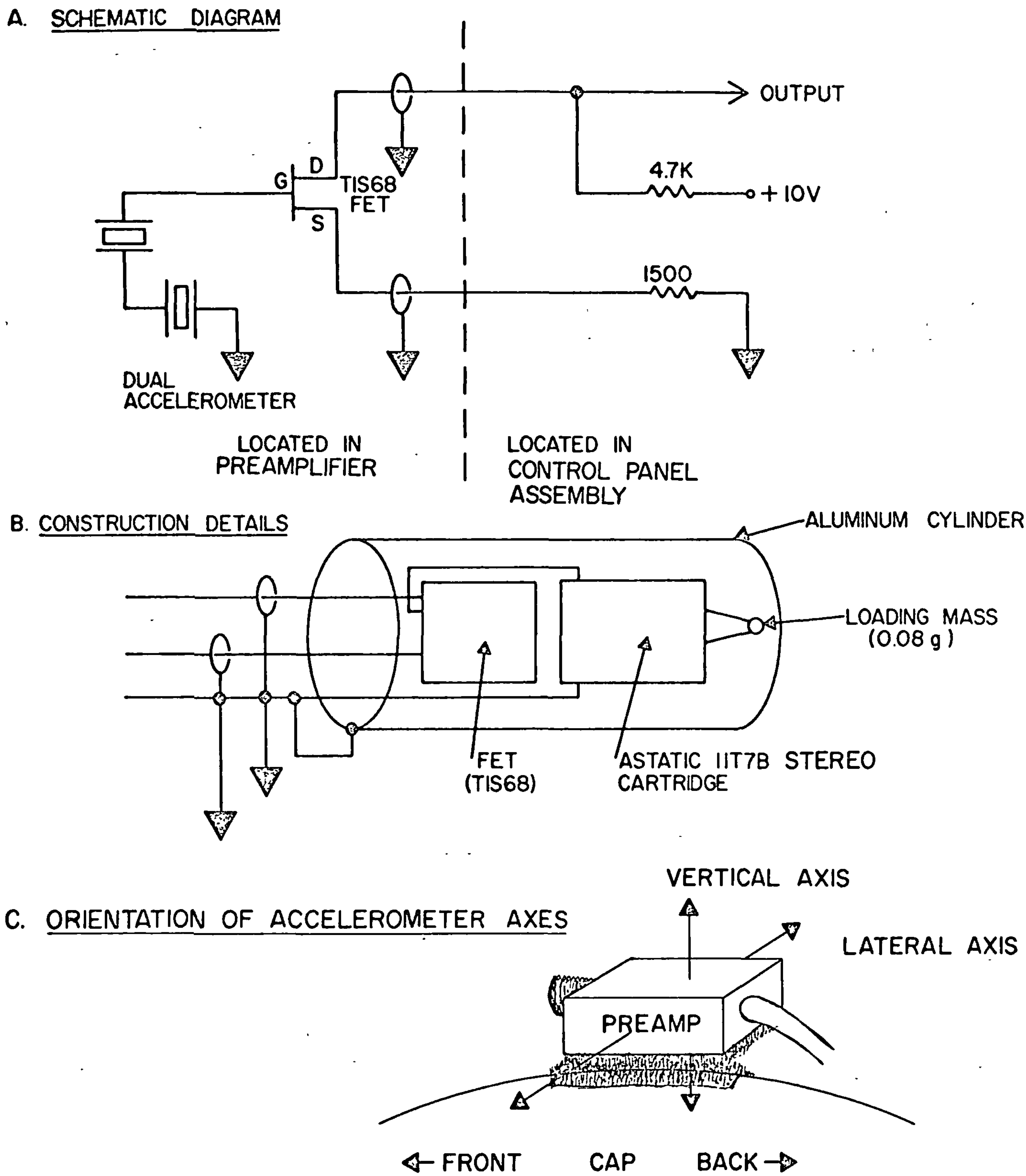


FIG. 15

DUAL ACCELEROMETER

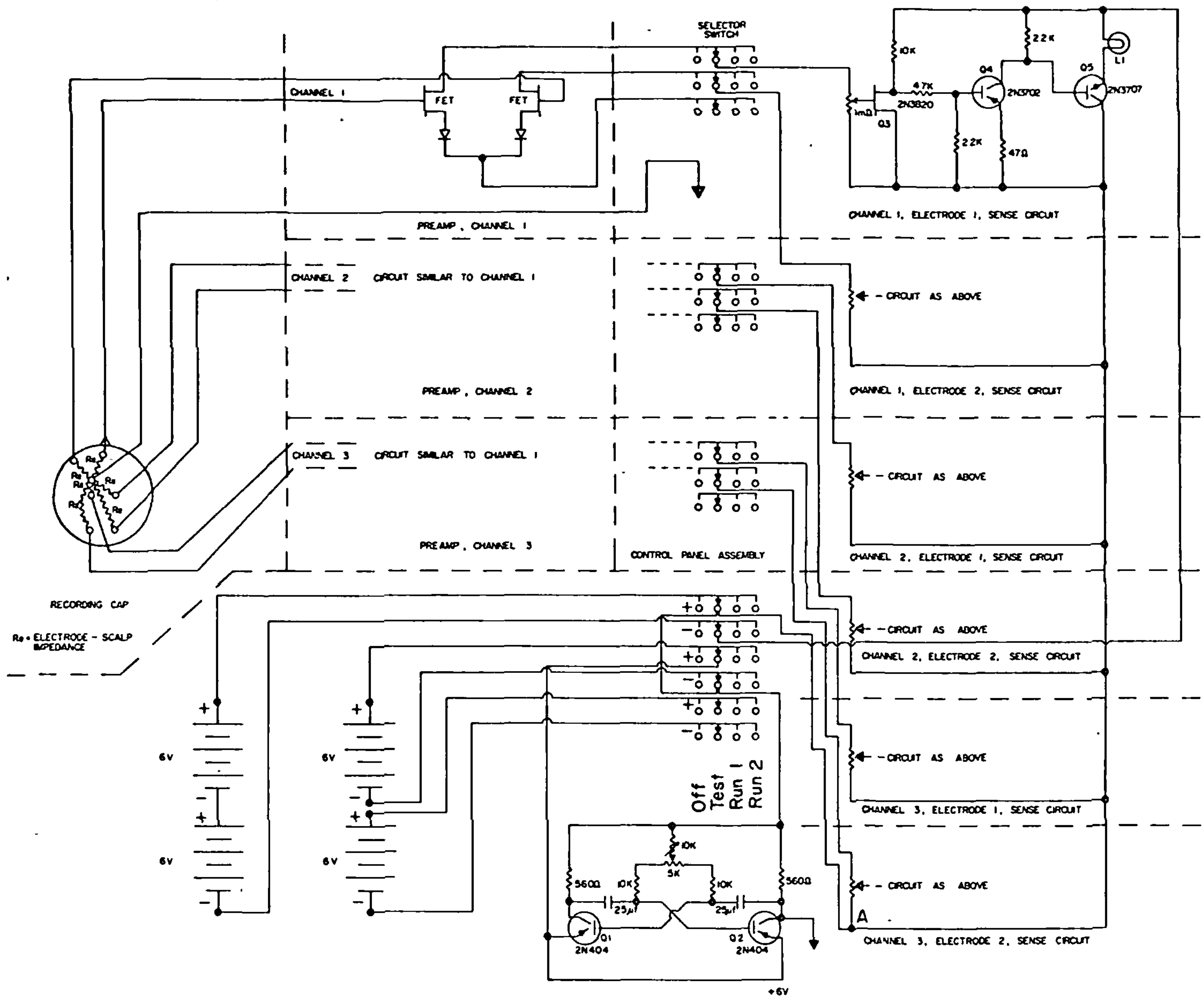


FIG 16
ELECTRODE TEST CIRCUIT

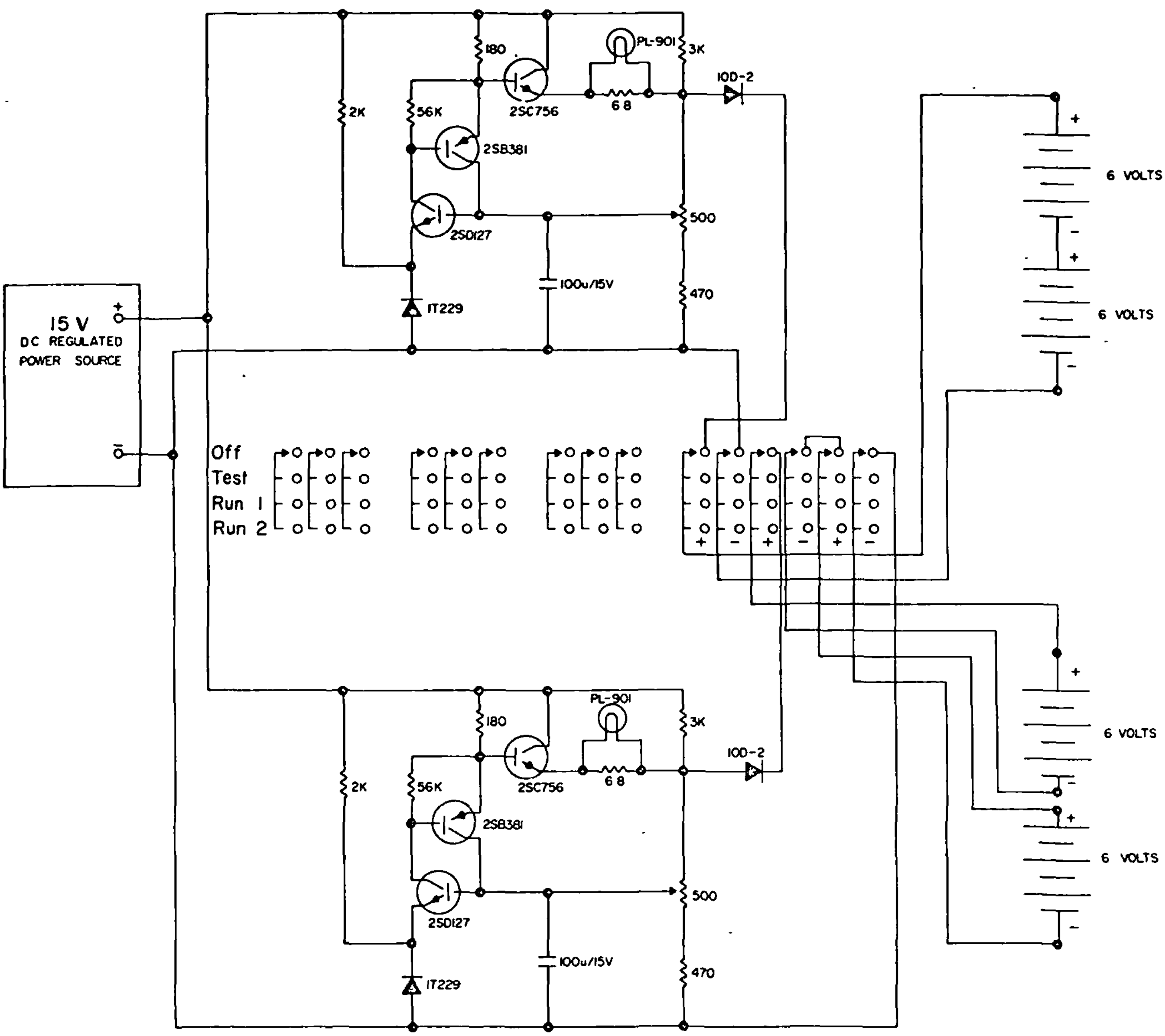


FIG. 17

POWER SYSTEM

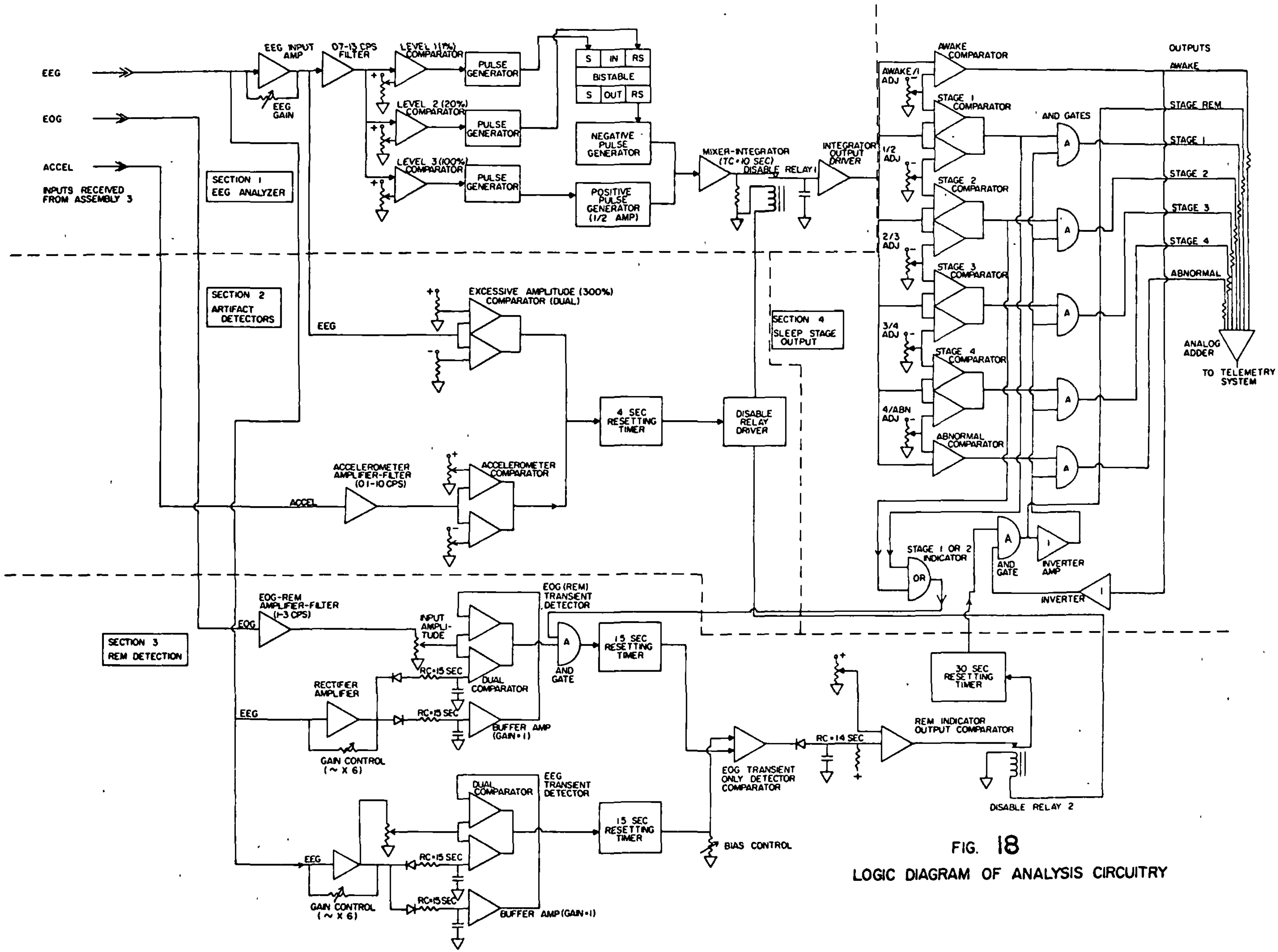


FIG. 18

LOGIC DIAGRAM OF ANALYSIS CIRCUITRY

SECTION 1 EEG ANALYZER
NEGATIVE PULSE GEN
WHITE FILTER
EEG IN
LEVEL 1 (1%) COMPARATOR
LEVEL 2 (20%) COMPARATOR
LEVEL 3 (100%) COMPARATOR (DUAL)
BISTABLE
Positive pulse generator
SECTION 2 ARTIFACT DETECTORS
ANALOG OUT
EXCESSIVE AMPLITUDE
ACCL COMPARATOR
ACCL IN
ARTIFACT ELIM TIMER
DISABLE RELAY DRIVER
TELEDYNE 712-9
SECTION 3 REM DETECTION
EOG AMP-FILTER (1-3 CPS)
LEVEL LOGIC REM
STROBE
EOG IN
REM TIMER
LEVEL SUPPRESSION
EOG ONLY TRANSIENT DETECTOR COMPARATOR
DISABLE RELAY
RECTIFIER AMP
BUFFER AMP
EEG TRANSIENT DETECTOR
DUAL COMPARATOR
1.5 SEC RESETTING TIMER
EOG AMPLIFIER FILTER
DUAL COMPARATOR EOG TRANSIENT DETECTOR
SECTION 4 SLEEP STAGE OUTPUT
ABNORMAL COMPARATOR
STAGE 4 COMPARATOR
STAGE 3 COMPARATOR
STAGE 2 COMPARATOR
STAGE 1 COMPARATOR
AWAKE COMPARATOR
Output to telemetry

Fig. 19

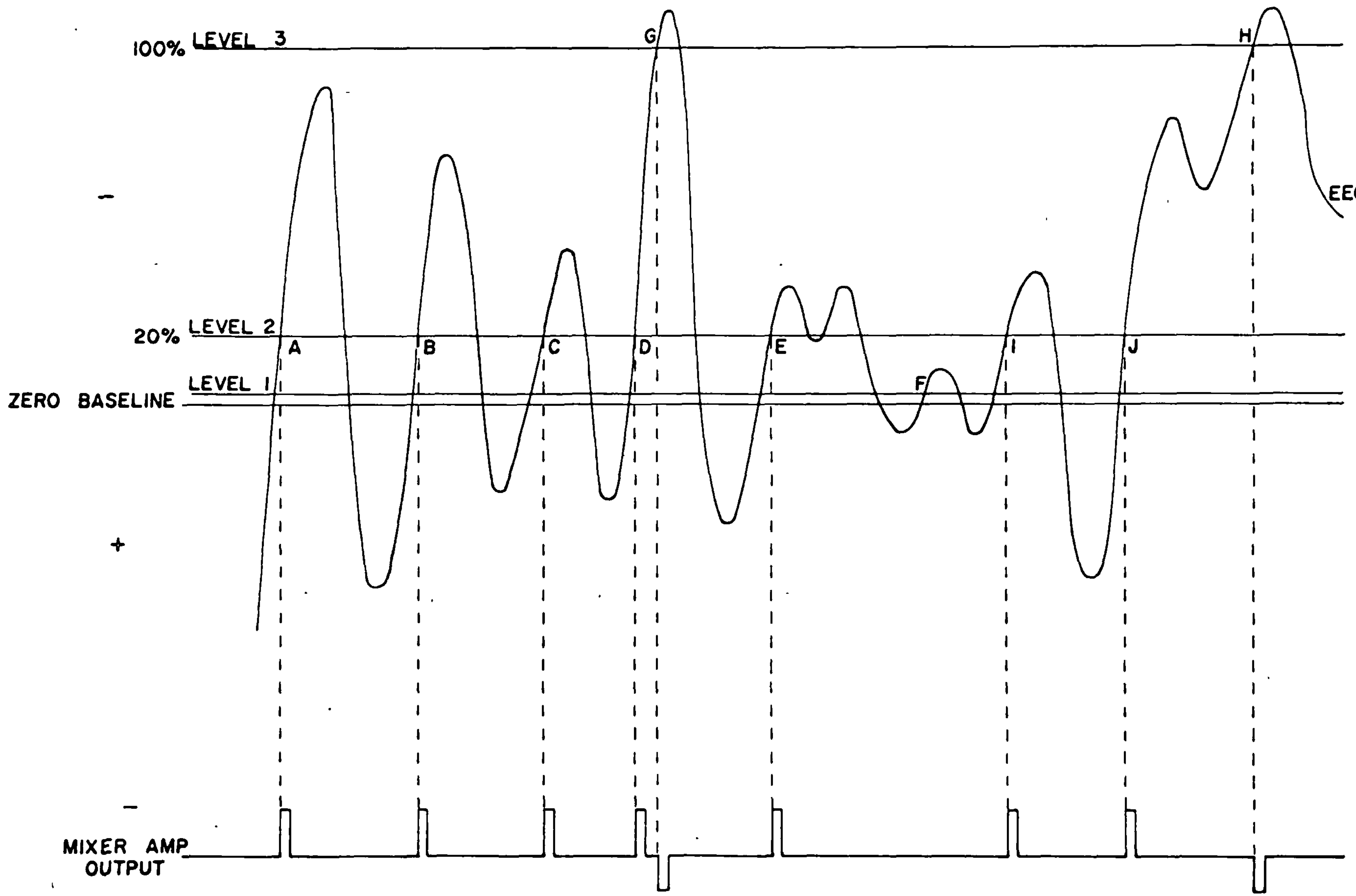
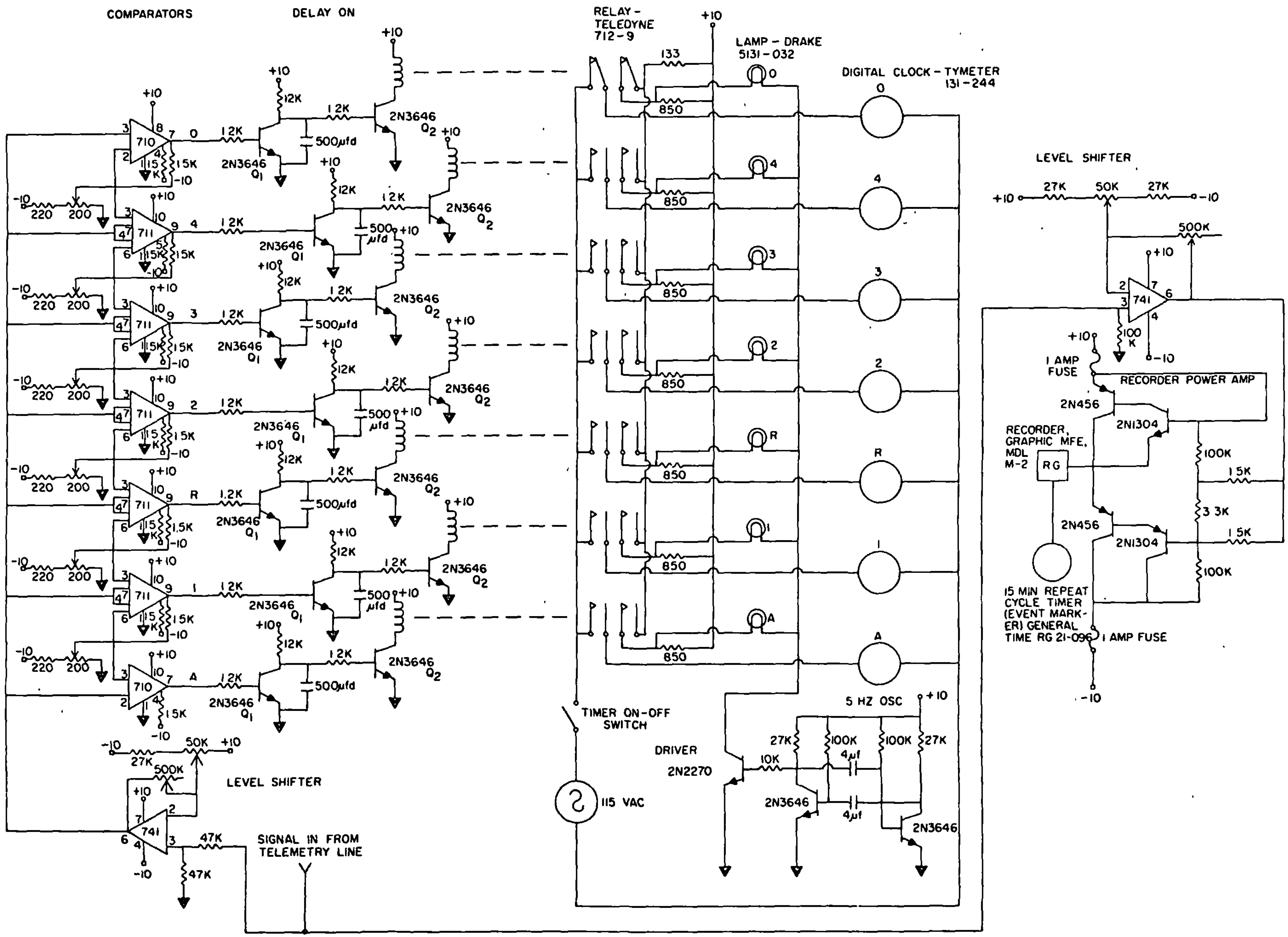

100%
LEVEL 3
G
H
EEG
20%
LEVEL 2
A
B
C
D
E
I
J
LEVEL 1
F
ZERO BASELINE
−
+
MIXER AMP
OUTPUT

FIG. 20



COMPARATORS
DELAY ON
RELAY - TELEDYNE 712-9
LAMP - DRAKE 5131-032
DIGITAL CLOCK - TYMETER 131-244
LEVEL SHIFTER
RECORDER POWER AMP
RECORDER, GRAPHIC MFE, MDL M-2
15 MIN REPEAT CYCLE TIMER (EVENT MARKER) GENERAL TIME RG 21-096
1 AMP FUSE
TIMER ON-OFF SWITCH
115 VAC
DRIVER 2N2270
5 HZ OSC
SIGNAL IN FROM TELEMETRY LINE
LEVEL SHIFTER

FIG. 21

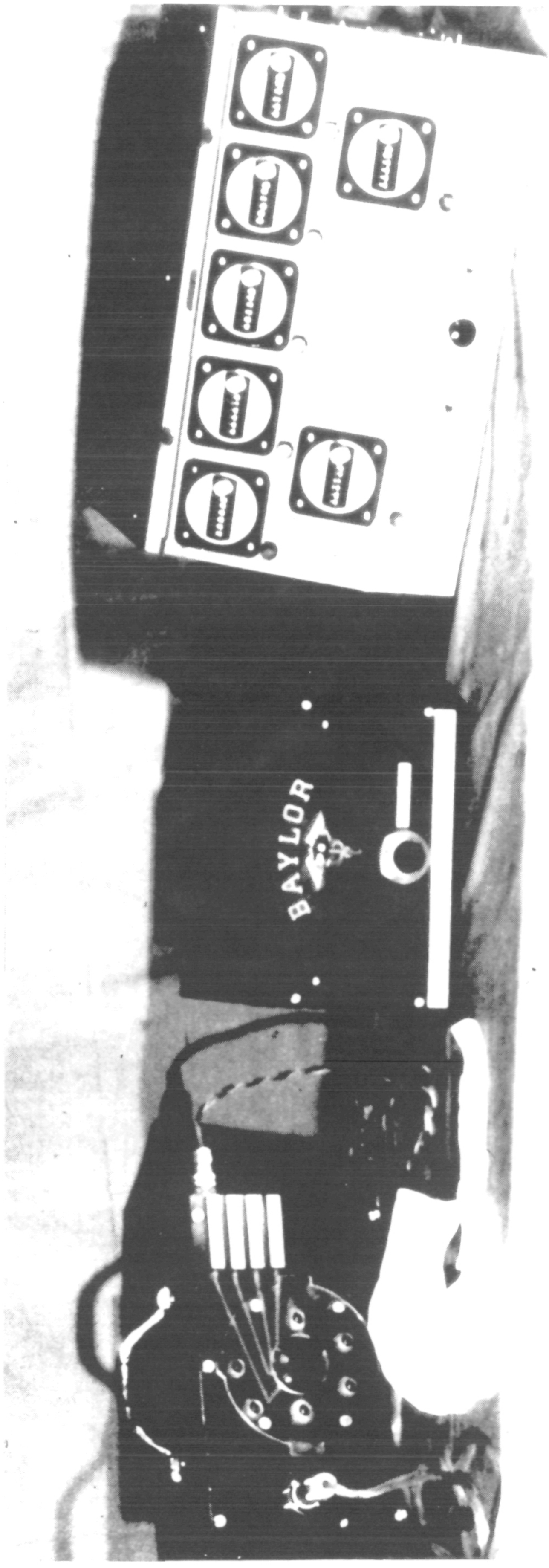


Fig. 22

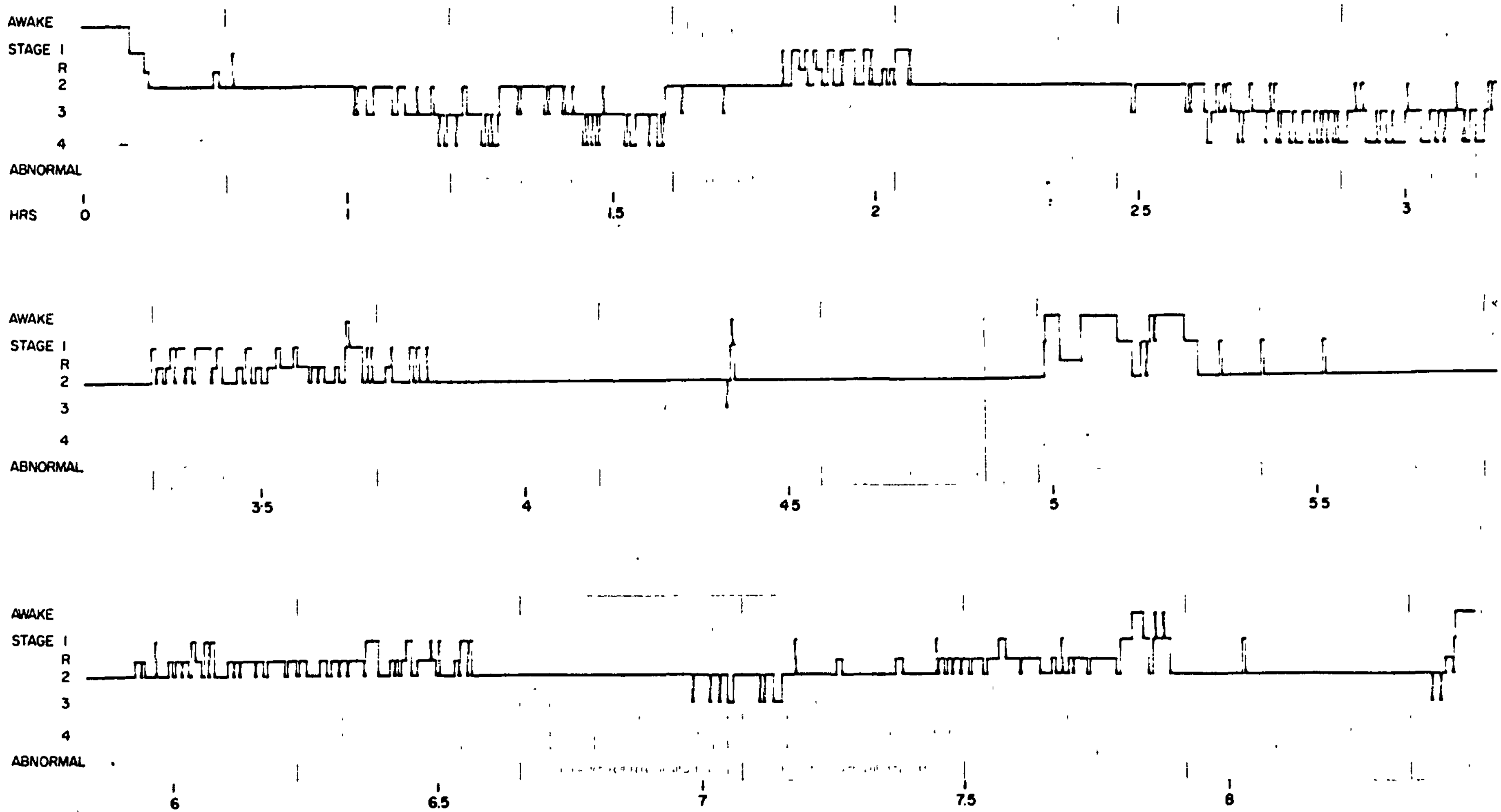


FIG. 23 – 8 HR. SLEEP PROFILE

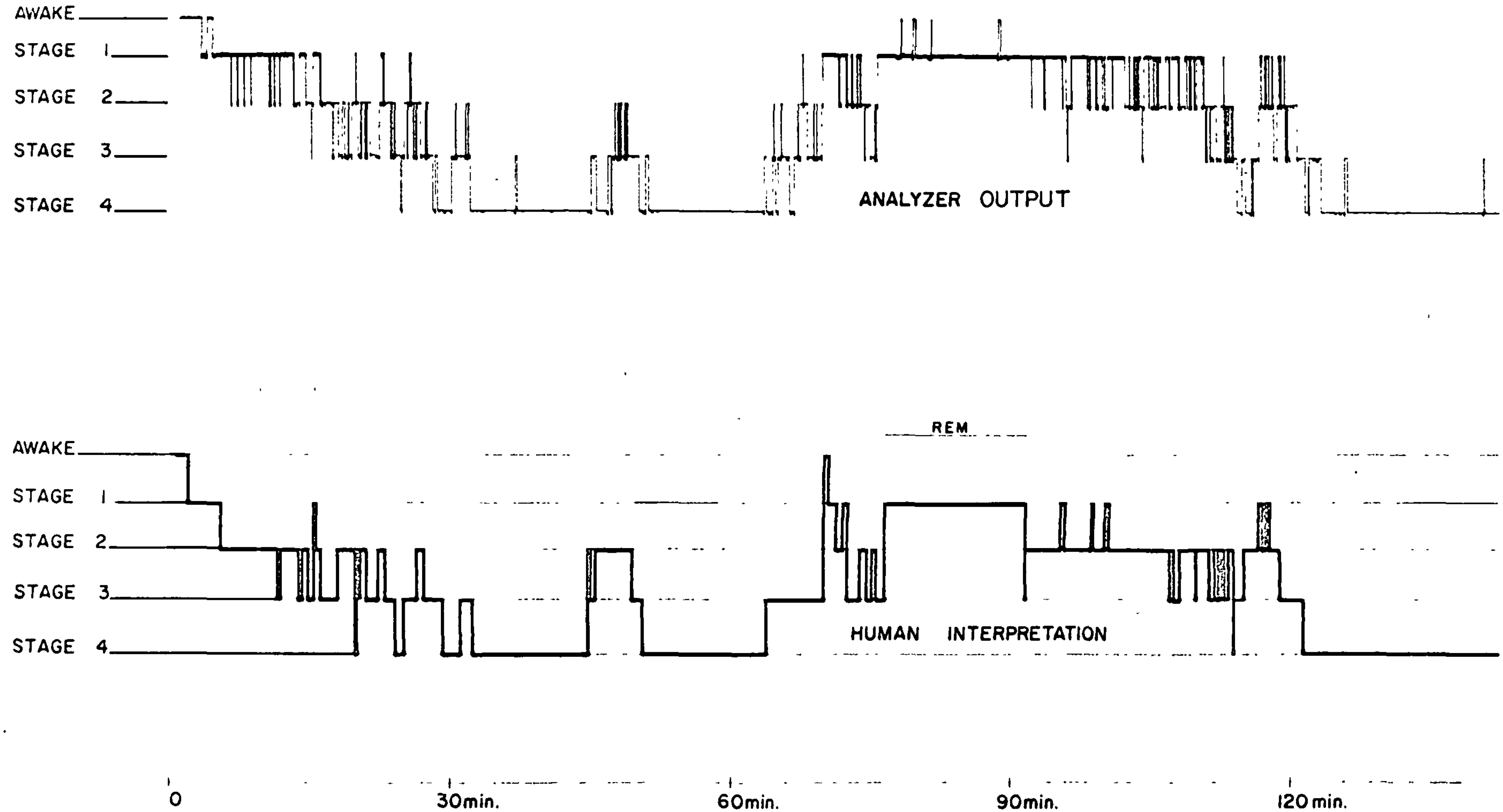

AWAKE
STAGE 1
STAGE 2
STAGE 3
STAGE 4
ANALYZER OUTPUT
REM
AWAKE
STAGE 1
STAGE 2
STAGE 3
STAGE 4
HUMAN INTERPRETATION
0
30min.
60min.
90min.
120 min.

FIG. 24

Table I.

Function Tested	EEG Preamplifier Input Conditions	EOG Preamplifier Input Conditions	Physical Condition of Preamplifier Assembly	Input Potentiometer Setting (Panel Assembly)	Special Constraints or Procedures	Telemetry Output Condition (Sleep Stage) at Time Specified from Onset of New Conditions at Input		
						After 60 sec		
EEG Analyzer and Output Comparators	50 μV, p-p, 5.3 Hz	Shorted	Stabilized	25 μV = 60%	None	Awake		
	" 4.9 Hz	"	"	"	"	1		
	" 4.1 Hz	"	"	"	"	1		
	" 3.8 Hz	"	"	"	"	2		
	" 2.6 Hz	"	"	"	"	2		
	" 2.25 Hz	"	"	"	"	3		
	" 2.1 Hz	"	"	"	"	3		
	" 1.8 Hz	"	"	"	"	4		
	" 0.75 Hz	"	"	"	"	4		
	" 0.6 Hz	"	"	"	"	0		
	" 0.0 Hz	"	"	"	"	0		
	" 10.0 Hz	"	"	"	"	Awake		
	" 4.5 Hz	"	"	25 μV = 150%	"	3		
Excessive Amplitude Comparator	20 μV, p-p, 5.3 Hz	"	"	10 μV = 60%	"	Awake		
	650 μV, p-p, 5.3 Hz	"	"	"	Transition to 650 μV from 20 μV must occur within 2 sec	Awake		
EEG and EOG Transient Detection	50 μV, p-p, 5.3 Hz	"	"	25 μV = 60%	None	Awake		
						5 sec after transient	25 sec after transient	60 sec after EEG change or 40 sec after transient
	" 5.3 Hz	200 μV, p-p, single 2.5 Hz transient	"	"	Begin output timing at EOG transient	Awake	Awake	Awake
	" 4.2 Hz	0	"	"	None	----	----	1
	" 4.2 Hz	200 μV, p-p single 2.5 Hz transient	"	"	Begin output timing at EOG transient	REM	REM	1

Table I. (continued)

Function Tested	EEG Preamplifier Input Conditions	EOG Preamplifier Input Conditions	Physical Condition of Preamplifier	Input Potentiometer Setting (Panel Assembly)	Special Constraints or Procedures	Telemetry Output Condition (Sleep Stage) at Time Specified from Onset of New Conditions at Input		
EEG and EOG Transient Detection						5 sec after transient	25 sec after transient	60 sec after EEG change or 40 sec after
	50 μV, p-p, 3.0 Hz	0	Stabilized	25 μV = 60%	None	----	----	2
	" 3.0 Hz	200 μV, p-p, single 2.5 Hz transient	"	"	Begin output timing at EOG transient	REM	REM	2
	" 2.2 Hz	0	"	"	None	----	----	3
	" 2.2 Hz	200 μV, p-p, single 2.5 Hz transient	"	"	Begin output timing at EOG transient	3	3	3
	" 4.2 Hz	0	"	"	None	----	----	1
	50 μV, p-p, 4.2 Hz $\xrightarrow{\Delta}$ 300 μV, p-p, 4.2 Hz Δ = time of EOG transient	200 μV, p-p, single 2.5 Hz transient	"	"	Begin output timing at EOG transient	1	2 or 3	3
	50 μV, p-p, 10.0 Hz	0	"	"	None	----	----	Awake
Accelerometer						After 60 sec		
	50 μV, p-p, 6.0 Hz	0	"	"	None	Awake		
	50 μV, p-p, 6.0 Hz $\xrightarrow{\Delta}$ 0 input signal Δ= time accelerometer motion begins	0	Motion of preamplifier (accelerometer) in vertical axis. Rate = 2 Hz, minimum; excursion = 6", minimum.	"	EEG signal goes to zero at time motion of preamplifier is begun (within 1 sec)	Awake		
	0	0	Stabilized	"	None	0		

Table II. Comparison of Human and Analyzer Sleep-Scoring Results

(Number of epochs scored and percent value indicated for each category)

Human Score	Automatic Analyzer Score: Awake	1	R	2	3	4
Awake	180 80%	11 5%	13 6%	19 8%	2 1%	0 0%
1	10 8%	59 45%	1 1%	60 46%	0 0%	0 0%
R	2 0.3%	71 12%	255 42%	274 46%	0 0%	0 0%
2	0 0%	5 0.5%	4 0.4%	961 91%	90 9%	7 1%
3	0 0%	0 0%	0 0%	132 42%	161 51%	21 7%
4	0 0%	0 0%	0 0%	4 3%	82 58%	55 39%